ENGINEERING GEOLOGICAL INVESTIGATIONS
AND HAZARD ASSESSMENT
FOR THE
PICTON, WAIKAWA AND SHAKESPEARE BAY AREA,
MARLBOROUGH SOUNDS.

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P. J. Horrey.

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ABSTRACT

The township of Picton, situated at the south-western corner of the Marlborough Sounds, is experiencing steady urban growth due to its servicing role and healthy tourism industry. The adjacent areas of Waikawa and Shakespeare Bay are identified as likely sites for future urban expansion. Increasing pressure for the development of less geotechnically favourable building sites has highlighted the need for improved engineering geological and geotechnical data on which to base land use planning decisions. This study provides an engineering geological assessment of the Picton, Waikawa and Shakespeare Bay catchments, and investigates the various geological hazards facing urban development in these areas.

The Mesozoic age Pelorus Group greywackes and Marlborough Schists underlying most of the study area are moderately to highly weathered, and landsliding is common on steeper slopes during periods of heavy rainfall. A number of generally north-east trending faults are mapped in the area, and a degraded surface trace of the Waikawa Fault is visible to the east of Picton. Investigations suggest that this fault has been active during the past 5000 years. Large volumes of alluvial gravels infill the lower catchment areas of Picton and Waikawa, and the resulting areas of low lying terrain are prone to flooding.

Engineering geological mapping utilising both air photograph interpretation and field mapping techniques was completed for the whole study area at 1:10000, and the Waikawa area only at 1:5000. These maps show bedrock geology, surficial deposits, and geomorphic features, and as such provide a guide to expected foundation conditions. Limited laboratory testing was also undertaken to characterise the geotechnical properties of weathered bedrock materials.

On the basis of engineering geological mapping, and site specific engineering geological investigation at scales of 1:50-1:1250, the hazardous geological processes potentially affecting the study area were identified as: landsliding, flooding, debris deposition, stream bank erosion, coastal erosion, ground subsidence and seismicity. Each of these processes were investigated, and engineering geological models formulated to synthesize field observations and interpretations.

A hazard map for the Waikawa residential area was compiled based on engineering geological mapping, and shows the areas potentially at risk from the above processes, together with estimates of the probability of occurrence of a hazardous event. Individual assessment of the hazards posed by each geological process was undertaken on the basis of the age and magnitude of most recent activity. Through examination of both the historical and geological record some estimate of the likely return periods for various hazardous events was possible.

A development suitability map was then compiled for the whole study area, based on engineering geological investigations and hazard assessment. This map indicates the extent of geotechnical limitations on future development, and as such is intended for use in the context of land use planning and administration. This map identifies a number of areas where extreme geotechnical limitations severely restrict future development, but also indicates the most favourable sites for urban expansion.

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CHAPTER 1
INTRODUCTION

1.1 BACKGROUND STATEMENT

The town of Picton, situated at the head of Queen Charlotte Sound (see Figure 1.1a), is steadily developing by virtue of an expanding tourism industry, and its role as the southern terminus of the Cook Strait road/rail ferry link. In the past urban development has progressed with limited regard for geological hazards. Increasing pressure for the development of building sites on less favourable terrain has highlighted the need for a better understanding of the geological and geomorphic processes responsible for landscape evolution in the area.

The high degree of weathering and complex deformation of local schist and greywacke bedrock materials, combined with a high annual rainfall, makes the area susceptible to flooding and slope movements. These processes have caused damage to engineering structures in the past, and continue to pose a hazard to urban development. This study adopts the engineering geology approach outlined by Bell and Pettinga (1984), which is felt to be the most effective means of (i) Identifying and delineating geological hazards, and (ii) Providing a land use zoning approach to enable development to proceed safely. Other examples of this approach include a stability assessment of Moeraki Township in North Otago (Molineaux, 1983), and an engineering geological assessment of the Havelock/Linkwater area (Kingsbury, 1987).

This project is the second (following Kingsbury (1987)) of what is hoped to be a series of similar investigations in areas of potential development throughout the Marlborough Sounds, completed on behalf of the Marlborough Catchment and Regional Water Board. It is intended that this study will assist the Board and other interested local authorities in ensuring the continued safety of urban development in the Picton/Waikawa area.

This study covers the three catchments of Waikawa Bay, Picton Harbour and Shakespeare Bay, although detailed investigations have been concentrated on the Waikawa residential area, which is the principal site of urban growth at present.

1.2 THESIS OBJECTIVES AND METHODOLOGY

The principal objectives of this study are as follows:

(i) To determine the spatial relationships and geotechnical properties of the various geological units in the catchments of Waikawa, Picton, and Shakespeare Bay.

(ii) To identify and delineate existing slope failures, and to determine failure mechanisms and causative factors with particular reference to structural and weathering properties of the underlying bedrock.

(iii) To identify and delineate other hazardous processes which may constitute a threat to urban development.

(iv) To prepare suitable hazard and land use zoning maps for residential development in the Waikawa area, such that the approach may be extended to the remaining two catchments at a later date.

This project is not concerned with the design of remedial measures for specific hazardous processes, but rather with the assessment of existing problems in order to develop sound planning policies for future development, based on the avoidance of problem areas.

With the above objectives in mind the following work programme was adopted:

<u>Phase 1 - Site Reconnaissance</u>
One months site inspection was carried out in consultation with the Marlborough Catchment Board during February 1988 in order to identify sites for detailed investigation.

<u>Phase 2 - Regional Engineering Geological Mapping</u>
Engineering geological mapping of the three catchments at a scale of 1:10000 using aerial photography and field mapping techniques was carried out during April - May, 1988.

<u>Phase 3 - Detailed Mapping, Logging and Sampling.</u>
Engineering geological mapping of the Waikawa residential area at a scale

of 1:5000 was undertaken during May - August, 1988. Descriptions and logs of key outcrops were also made during this period, and samples were collected for laboratory analysis.

Phase 4 - Laboratory Testing.

A laboratory geotechnical testing programme, designed to characterise the physical and mineralogical properties of geological materials in the study area, was completed during September - December 1988. Some supplementary sampling and field testing was also undertaken at this stage.

Phase 5, Thesis Preparation.

The remaining months until June 1989 were occupied with field checking, thesis preparation, and drafting of final plans.

1.3 DESCRIPTION OF STUDY AREA.

1.3.1 Geological Setting

The Picton-Waikawa area is underlain by deeply weathered Mesozoic greywackes of the Pelorus Group (Beck, 1964). To the west of Picton Harbour (see Figure 1.1b) the greywackes are in fault contact with Mesozoic schists, while to the east of Waikawa township there is a gradual transition back to low grade schist. Small areas of Tertiary marginal marine sedimentary rocks outcrop at the head of Shakespeare Bay and near The Elevation, just south of Picton (Beck, 1964).

The Lower Picton and Waikawa catchments are infilled with extensive coarse alluvial gravels, the majority of these being deposited since the last glaciation.

1.3.2 Physiography

The majority of the study area consists of densely vegetated steep slopes (25-45°) rising to the Robertson Range (altitude 1000 metres) to the south and east, and Mount Freeth (altitude 600 metres) to the west (see Figure 3.1, map pocket). The three major catchments follow the northeast-southwest structural alignment of the region. While drainage

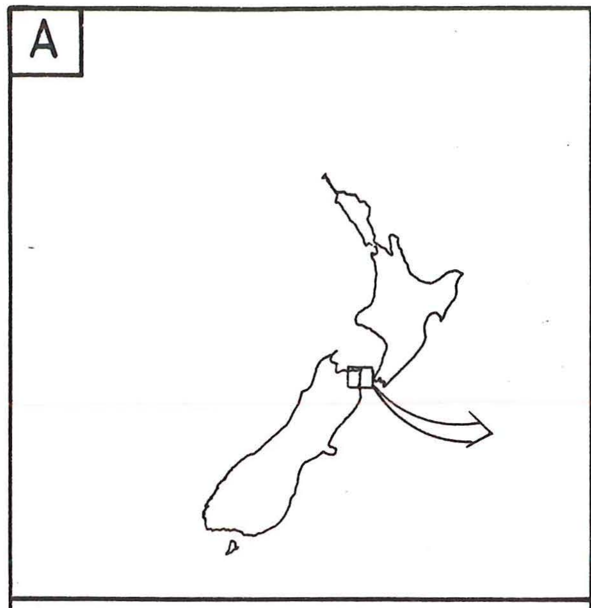


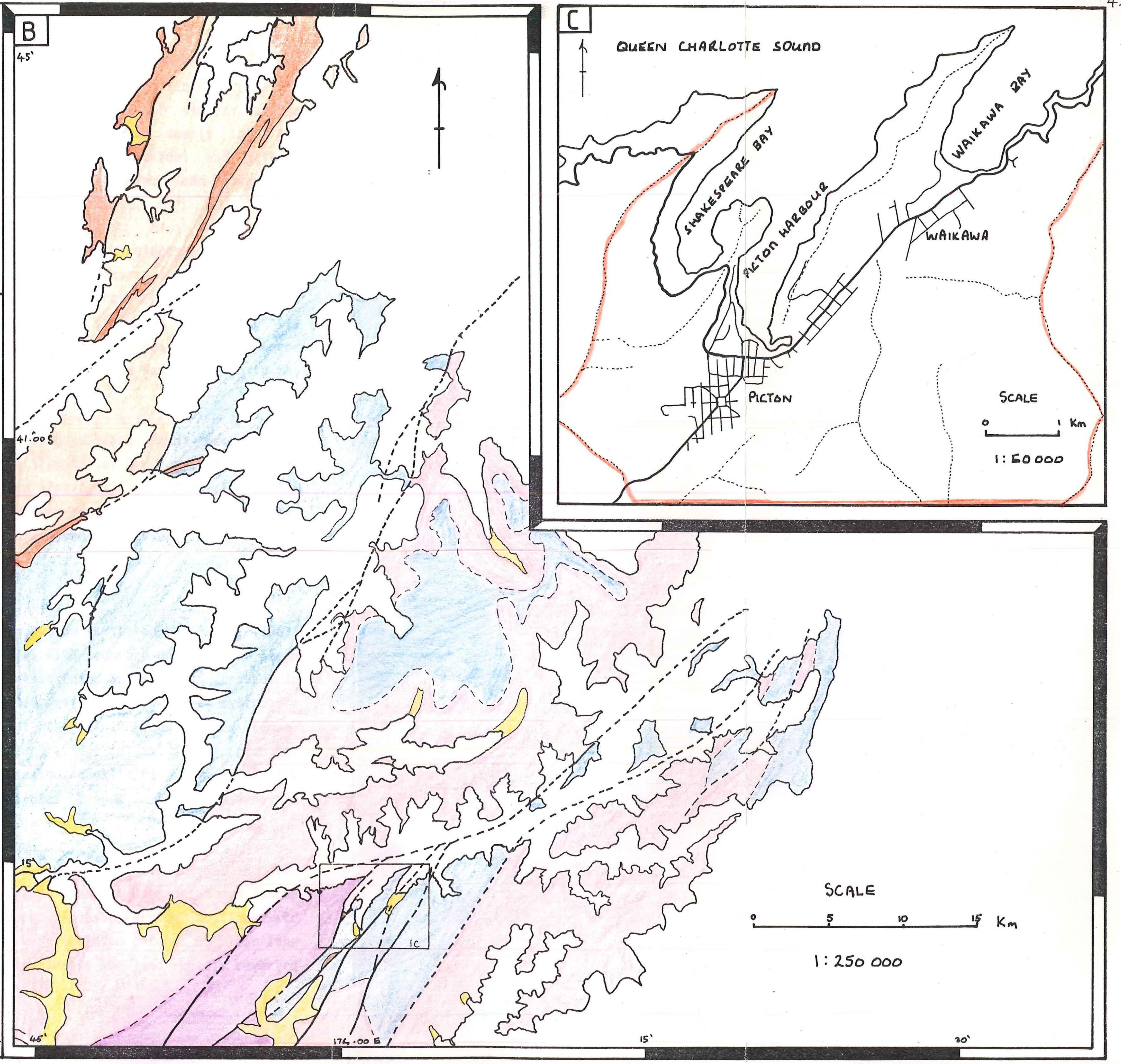
FIGURE 1

REGIONAL GEOLOGY AND LOCATION DIAGRAM

LEGEND

- ALLUVIUM : HOLOCENE
- SANDSTONE MUDSTONE CONGLOMERATE LANDON
- GRANODIORITE INTRUSIVES MESOZOIC
- TUFFACEOUS SEDIMENTS, INTRUSIVES. BROOK STREET GROUP : MESOZOIC
- GREYWACKE ARGILLITES PELORUS GROUP : MESOZOIC
- CHLORITE II SCHIST MARLBOROUGH SCHIST: MESOZOIC.
- CHLORITE III SCHIST
- FAULT DEFINATE
- FAULT INFERRED
- GEOLOGICAL CONTACT: DEFINATE
- GEOLOGICAL CONTACT: INFERRED

SIMPLIFIED AFTER BECK (1964)



patterns in the study area are undoubtedly influenced by bedrock structure, complex deformation of bedrock makes it difficult to quantify this relationship. Drainage patterns on the steeper slopes have a dendritic appearance, with streams being incised deeply into the weathering profile. Alluvial gravels from the Waitohi and Waikawa Streams have infilled the heads of Picton Harbour and Waikawa Bay respectively, creating extensive areas of flat land.

Despite the rapid changes in relief between bedrock slopes and alluvial flats, large scale development of alluvial or debris fans is restricted to (i) The south-western margin of the Waikawa residential area, where alluvial fans from several catchments have coalesced to form a gently seaward sloping surface. (ii) The western side of Shakespeare Bay, where a series of debris flow events have formed a large fan extending to the shoreline.

The eastern arm of Picton township (along Waikawa Road) occupies an elongate depression underlain by a low relief bedrock surface, which contrasts markedly with the surrounding area (see Figure 2.9). The linear nature of this depression suggests strong tectonic control on landscape development. This feature is further discussed in section 2.5.1.

1.3.3. Land Use and Vegetation.

Vegetation cover prior to European occupation is stated by Bowie (1963) as being kamahi-rewa rewa communities with podocarp-boadleaf and beech podocarp predominating. Although the first European settlers arrived in the 1850's (Kelly, 1976), it was not until the 1880's that systematic burning off of steeplands throughout the Marlborough Sounds began. Deforestation and subsequent stock grazing initiated a period of accelerated soil erosion and shallow seated landsliding, and many of the shallow regolith and colluvial failures mapped in the study area are attributed to this.

Farming continued to provide a satisfactory living for those involved until the Depression of the 1930's, when economic considerations forced the abandonment of many of the steeper slopes. Farming continued to decline steadily, and today only very isolated patches of clear land remain (Kelly, 1976). Once abandoned by farmers the land rapidly reverted to secondary growth of such species as manuka, tawhine, piripiri, Spannish heath, bracken and gorse, the last named being prevalent. As accidental bush fires are common in the Picton area it is likely to be some time before regeneration of beech forest takes place.

The past twenty five years has seen large parts of the Sounds planted in exotic pine forest. Planting in the Picton area has so far been limited to the eastern side of Shakespeare Bay, and the areas north and east of Queen Charlotte College in Picton. The latter area was clear felled during the mid 1980's. As the local soils are generally of poor fertility, and flat land is scarce, the Picton area is generally unsuitable for cropping or market gardening.

1.3.4 Climate

As New Zealand lies in the Southern Hemisphere Temperate Zone, Marlborough's weather is dominated by eastward moving anticyclones and intervening troughs of low pressure. Most of the Province experiences a significant rain shadow due to its location east of the main divide, and is one of the driest regions in New Zealand (Pascoe, 1983). The Marlborough Sounds area, however, receives a significantly higher rainfall than the rest of Marlborough, with Picton experiencing an average annual rainfall of between 1200 and 1600 mm (Pascoe, 1983). Boyce (1971) noted that Picton receives its maximum rainfall during March, with October and November being the driest months. Bowie (1963) recognised a secondary rainfall maximum in June and July. Table 1.1 lists monthly and annual rainfall normals for the study area.

The prevailing wind in the Picton area is from the north, with spring and summer being the windiest periods. In spite of Picton's coastal location, frosts are common during the winter months. Temperatures in excess of 25°C are experienced during the summer.

1.3.5. Urban Development

For the purpose of this study the term "urban development" is used in its wider sense to refer to building construction or engineering works associated with a population centre.

TABLE 1.1 RAINFALL NORMALS FOR RECORDING STATIONS WITHIN THE STUDY AREA, 1951-1980.

STATION	LAT.	LONG.	ELEV.	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
FREEZING WORKS	41 17S	174 00E	30	83	65	90	125	151	125	143	151	103	118	95	85	1334
PICTON (WAIKAWA)	41 16S	174 02E	-	96	77	107	114	129	120	203	129	105	108	95	87	1370
PICTON (COLLEGE)	41 17S	174 01E	30	90	57	118	132	154	138	145	170	104	118	98	87	1411
PICTON No. 2	41 17S	174 01E	30	95	78	112	138	162	125	149	160	115	122	100	109	1465
PICTON	41 18S	174 00E	6	86	67	99	126	115	138	170	166	109	131	98	94	1435
PICTON SOUTH	41 18S	174 01E	23	96	88	118	130	193	168	223	224	124	143	107	134	1748

The town of Picton was founded in 1848, and initially flourished as the seat of provincial government for Marlborough, and as a service community for farming interests in the Sounds. Picton has experienced a steady population growth since the 1920's, with the opening of the Picton-Christchurch railway in 1945 and the initiation of the roll-on roll-off ferry service in 1965 being important contributing factors. Picton has a population of 3220(1981 figures).

Urban development was largely confined to the lower Picton catchment until the mid 1970's, when a lack of suitable building sites transferred attention to Waikawa. The past decade has seen a rapid increase in residential development at Waikawa, with the introduction of a reticulated sewage system and improvements in water supply services. The Waikawa residential area, previously under the jurisdiction of the Marlborough County Council, was annexed to the Picton Borough on the 1st of April, 1984.

The construction of the Waikawa marina by the Marlborough Harbour Board during 1985-6 has been a further catalyst for urban development, with a number of retail, tourist, and accommodation developments planned to cater for the expected large numbers of visitors during the summer holiday season.

There is little urban development in Shakespeare Bay at present, as all the available land is owned by Port Marlborough New Zealand Ltd. (the commercial division of the Marlborough Harbour Board), which intends to develop the Bay as a port facility. This project is still in the planning stages, but it is tentatively scheduled to begin in the mid 1990's.

1.4 INVESTIGATION METHODOLOGY

1.4.1. General

Engineering geological investigations for this project fall in to the following three categories, based on the scale of investigation.

(i) Regional, comprising engineering geological mapping of the whole study area at a scale of 1:10000 (Figure 3.1, map pocket).

(ii) Local, which includes engineering geological and hazard zonation mapping of the Waikawa Residential Area at a scale of 1:5000 (Figures 3.2 and 4.1, map pocket).

(iii) Site Specific (scales up to 1:1250), involving detailed exposure logging and description, sampling, and field testing at selected sites. The above approach allows the collection of detailed data on specific aspects of the engineering geology of the study area. This information may subsequently be extrapolated, in conjunction with local and regional mapping, to provide an engineering geological database for the whole study area.

All important localities referred to in this text are given a locality number, and are shown on Figures 3.1 or 3.2 (map pocket). All grid references quoted in this thesis refer to the NZMS 260 1:50000 sheet P27, "Picton".

1.4.2 Engineering Geological Mapping

Engineering Geological maps of the whole study area (1:10000, Figure 3.1), and of the Waikawa residential area (1:5000, Figure 3.2), were compiled by air photograph interpretation, with field verification of important features where terrain permitted. The main objectives of these maps (after Bell and Pettinga, 1985) are:

(i) To indicate both bedrock and surficial geology.

(ii) To identify and delineate relevant geomorphic features and processes, with particular attention to slope movement problems.

Important cultural features such as roads and administrative boundaries are also indicated, as are localities at which further detailed investigation was undertaken.

1.4.3. Field Investigations and Sampling

Following the completion of engineering geological mapping, field investigations for this project primarily involved the description and logging of key exposures throughout the Waikawa residential area. During logging a number of bulk samples of both soil and rock material were taken for later laboratory testing.

Penetrometer testing, hand auger holes and shallow seismic refraction profiling were also employed as site specific investigation methods, and are discussed further as such in section 3.2.

1.4.4. Laboratory Geotechnical Testing

A laboratory programme of geotechnical testing was undertaken to characterise the engineering properties of the bedrock, regolith, and colluvial material found in the Waikawa area. This programme follows similar work on characterisation of weathered greywacke regolith/colluvium in the Claverly-Oaro region of North Canterbury (Luxford and Bell, 1981), and the characterisation of low grade schist regoliths in the Havelock area (Kingsbury, 1987).

Weathered greywacke bedrock samples were tested for grain size distribution, in-situ water content, Atterberg limits, and X-ray diffraction determination of clay mineralogy. Rock strength testing was also carried out on greywacke bedrock samples using both point load testing (ISRM, 1984), and cone indenter methods (MRDE, 1977).

1.4.5 Geological Hazard Assessment

Geological hazard mapping and zonation is now widely used overseas as an aid to urban planning, although it has seen limited application in New Zealand to date. This study concentrates on detailed hazard mapping of the Waikawa residential area, as this has been identified as a major site for future urban development.

The main hazardous processes with the potential to endanger urban development are slope movements, flooding, debris deposition, ground subsidence, stream bank erosion, and coastal erosion. A <u>Hazard Zonation Map</u> (Figure 4.1, map pocket) for the Waikawa residential area at a scale of 1:5000 shows the areal extent of each hazardous process, and assigns a degree of hazard to each zone so defined.

From this information a Development Suitability Map (Figure 4.2, map pocket) at a scale of 1:10000 has been compiled. This map zones the whole study area in terms of four land suitability classes on the basis of the extent of geological and geotechnical limitations to residential subdivision and development.

1.5 THESIS ORGANISATION

Following this introduction, Chapter 2 discusses the geology and geomorphology of the study area with reference to geological history, materials and processes. Chapter 3 outlines the engineering geological and geotechnical investigations undertaken for this project, and develops site models encompassing slope movements, bedrock weathering, alluvial deposition and active faulting.

Chapter 4 backgrounds geological hazard and land use zonation practices, both in New Zealand and overseas, and a hazard zonation approach for the Picton area is proposed, based on information presented in Chapters 2 and 3. This approach is then compared with existing practices, both in New Zealand and overseas.

Chapter 5 summarises the project and presents the principal conclusions, together with recommendations for further investigations within the Picton region. Technical data and material not directly related to a specific section of the text is included in the appendices.

CHAPTER 2
GEOLOGY AND GEOMORPHOLOGY

2.1 INTRODUCTION

This chapter outlines the geological and geomorphological setting of the study area. As there is a large amount of literature on these topics concerning the Marlborough Sounds generally, this chapter discusses only information directly relevant to the Picton, Waikawa and Shakespeare Bay areas. In addition to a discussion of geologic and geomorphological history and processes, descriptions of the various geological units are also included at this stage.

The terms "rock" and "soil" are defined differently in the fields of geology and engineering. The geological usage of these terms is adopted for this study. Rock material is defined as:

> "any material below the depth of modern weathering, regardless of degree of consolidation or cementation", and is "classified in terms of mineralogy, texture, and assumed mode of origin."
> (Bell and Pettinga, 1983)

Soil material is defined as:

> "material formed at the earths surface, by physical, chemical, and biological processes", and is "classified by mineralogy, texture, chemistry etc."
> (Bell and Pettinga, 1983)

For the purposes of this study," bedrock" is defined as the first unit of pre-Quaternary age rock material encountered beneath the ground surface. The term "surficial geology" refers to rock and soil material overlying bedrock, and outcropping at the surface. Thus surficial geology dictates the foundation requirements for residential structures.

Both "geological" and "engineering" properties are described for the various bedrock and surficial geological units defined for the study area. Geological descriptions cover structure, texture, mineralogy, and mode of origin, while engineering descriptions concentrate on geotechnical properties. Engineering descriptions follow the scheme outline by Bell and Pettinga, (1984) (see Appendix 1).

2.2 PREVIOUS WORK

Early literature concerning the geology of the study area was centred on the discovery of coal at the base of the Tertiary sequence in Shakespeare Bay. Contemporary accounts of the local geology are given by Mackay (1879, 1881, 1882), Hector (1882, 1894) and Morgan (1915, 1920). After several attempts between the 1880's and 1920's, mining proved uneconomic, and subsequent geological work in the area has been limited. The only published geological map to cover the study area in any detail is the New Zealand Geological Survey 1:250 000 sheet No. 22, by Beck (1964). Regional distribution of soil types is represented on a similar scale map, Soil Map of New Zealand sheet 2, by Vucetich (1965), and Land Resource Inventory Sheet No. 22 (MOWD, 1976) provides additional information on land use, slope, and soil type. Vitaliano (1968) described the structure and geochemistry of the inner Queen Charlotte Sound, and a recent study by Nicol (1988) included detailed mapping and structural analysis of the Shakespeare Bay and Mount Freeth area. Brown (1981b) gives descriptive logs for a number of water wells and foundation investigation test bores in the lower Picton catchment, although the information is not sufficiently detailed to be of use at the scale of this project.

Although a large number of consultants reports have been prepared dealing with specific civil engineering projects, there is little published information dealing specifically with the engineering geology of the study area. Paterson (1981) investigated the stability of rock slopes on the west shore of Picton Harbour adjacent to the Golden Bay Cement Company's cement silo. Coleman (1973) reported on the stability of several proposed subdivision sites in upper Kent and Otago Streets, upper Wairau Rroad, upper Scotland Street and Gravesend Place. A report commissioned by the Marlborough Harbour Board (Brickell et al, 1976) outlines the site investigations carried out at the head of Shakespeare Bay for a proposed new port facility.

A number of authors have considered the geomorphology of the Sounds, but again there is little specific reference to the Picton area. Cotton (1925) discussed the geomorphic evolution of the Sounds, and advocated the theory of the Sounds as a Northwest tilting block to account for the drowned appearance of the landscape. Winslow (1966) postulated that the

Sounds were a series of raised submarine canyons, citing the existence of similar features discovered offshore to the north as supporting evidence. This theory was refuted by Soons (1968). W. Lauder (1969) discussed the possibility of a reversed ancient drainage system, in which the rivers flowed from north-west to south-east, toward the Wairau Plain. Geomorphic and bathymetric evidence was cited in support, although this has been questioned by G. Lauder, (1987). Recent workers have tended to dispute the hypothesis of a tilting Sounds 'block', and attribute the inundation of the Sounds to post glacial sea level rise alone (Esler 1984, Kingsbury 1987, G. Lauder 1987). Further discussion and literature reviews concerning the geomorphology of the Marlborough Sounds in general are given by Esler (1984), Smith (1987), Kingsbury (1987), G. Lauder (1987).

2.3 BEDROCK GEOLOGY

2.3.1 Pelorus Group Rocks

2.3.1.1 Distribution and Age

The greywackes and argillites (slightly metamorphosed sandstones and mudstones) that underlie the Picton/Waikawa area have been correlated with Pelorus Group rocks in Nelson (Nicol, 1988; Beck, 1964), and with Caples Group rocks found in Southland (Turnball, 1979). These rocks are in faulted contact with Marlborough Schist directly to the west of Picton Harbour. To the east of Waikawa township a weak foliation is observed in Pelorus Group greywackes. There is a gradual transition further east to low grade schists. Nicol (1988), on the basis of limited fossil evidence, considered the Pelorus Group rocks to be of Late Permian to Triassic age.

2.3.1.2 Description

(i) Geological Properties

Nicol (1988) identified two different suites of Pelorus Group rocks in the Picton area, and differentiated these on the basis of arenite composition. Boundary relationships, however, proved too complex to be accurately defined. Pelorus Group rocks consist of massive, fine to coarse, moderately well sorted sandstones, with occasional alternating sandstone/mudstone horizons, and very occasional massive mudstone beds. Arenite composition is dominated by feldspars and volcanic lithic fragments, with lesser amounts of quartz. Mineral alteration is extensive, and quartz-prehnite veins are common (Nicol, 1988).

(ii) Engineering Properties

The rock mass is complexly deformed, and contains closely spaced, irregular joints and fractures. With the exception of argillaceous horizons, bedding does not exert a significant control on discontinuity orientation. The rock is weathered at the surface to grade V or VI, and is moderately strong to moderately weak (after Bell and Pettinga, 1983). The rock is typically dark yellow-brown, with dark brown iron staining common on fracture surfaces. This material compacts well, and has been used extensively for both terrestrial fill and marine reclamation in the Picton area.

2.3.2 Marlborough Schist

2.3.2.1 Distribution and Age

Low grade schists of chlorite 2-3 textural zone underlie the peninsula separating Picton Harbour and Shakespeare Bay. There is a gradual increase in metamorphic grade toward the west (chlorite 4 textural zone schists predominate in the vicinity of Mt. Freeth). Beck (1964) assigned a Carboniferous age to these rocks, but later work, summarised by Nicol (1988), suggests that the schists were formed during the Rangitata Orogeny, therefore constraining the age to Late Triassic or Early Jurassic.

2.3.2.2 Description

(i) Geological Properties

The lower grade schists on the Eastern side of Shakespeare Bay are predominantly muscovite-quartz schists, while the higher grade rocks to the west of the Bay exhibit a greenschist assemblage containing albite, quartz, muscovite, clinozoisite and tremolite/actinolite (Nicol ,1988).

Although schistosity generally dips steeply to the west, the schists are often extensively deformed in outcrop, and contain many irregular fractures infilled with quartz.

(ii) Engineering Properties

These rocks are moderately to highly weathered in outcrop giving a characteristic mid yellow colour, and are typically jointed and fractured. The schist is suitable as hard fill and for armouring purposed in its unweathered form, although this is difficult to obtain in the study area. In the past unweathered schist from Koromiko and Pukaka Valley south of Picton has been used for these purposes.

Failure along schistosity is common, especially in the higher grade schists on the western side of Shakespeare Bay, where foliation is well developed, and mineral segregation extensive.

2.3.3 Tertiary Rocks

2.3.3.1 General

Isolated outliers of Tertiary sediments occur at the head of Shakespeare Bay, and immediately west of State Highway 1 at The Elevation, (grid reference P27, 925 885) just south of Picton (Beck, 1964). Three formations are recognised, and are thought to be the in-faulted remnants of a lagoonal or inner shelf sedimentary basin deposited in Oligocene times. All the formations described below are highly weathered in outcrop, and are generally overlain by 1-2 metres of mixed colluvium. Faulting and folding have extensively disturbed the sedimentary structure of these rocks, and a lack of fresh outcrop makes it difficult to accurately define the boundary relationships of the various formations. Microfossil evidence suggests a Landon (Lwh) age for these rocks, which have been mapped and studied in detail by Nicol (1988). The following descriptions are based on his work.

2.3.3.2 Picton Conglomerate

The Picton Conglomerate formation is restricted to the eastern side of Shakespeare Bay, extending as far north as the old freezing works site.

This basal unit of the Tertiary sequence consists of an indurated conglomerate containing angular, cobble sized clasts derived from the Pelorus Group rocks, with occasional sandstone horizons. There is a general increase in matrix carbonate content and an overall decrease in grainsize toward the top of the formation. The conglomerate rests unconformably on Pelorus group basement, and this contact is visible on the shore platform on the eastern side of the Bay. The indurated nature of the conglomerate suggests it would be suitable for fill.

2.3.3.3 Elevation Mudstone.

This formation is observed to outcrop at the top of The Elevation, and is found on both the eastern and western shores, near the head of Shakespeare Bay. The massive, grey, poorly indurated mudstone contains quartz, illite, muscovite, and abundant microfossils. Isolated, discontinuous lenses of bituminous "A" rank coal are found within the mudstone in Shakespeare Bay, and have been the subject of several mining ventures in the past, all of which eventually proved uneconomic.

2.3.3.4 Shakespeare Bay Sandstone.

The uppermost unit in the Tertiary Sequence is a moderately well sorted, poorly indurated, quartz rich sandstone containing occasional conglomeratic horizons. Very occasional cemented calcareous fossilliferous horizons are also present. This formation is observed in outcrop along Queen Charlotte Drive at the Head of Shakespeare Bay, and along the shore platform to the east of the Bay. The poorly indurated nature of this material suggests it would not perform well as fill.

2.3.3.5 Engineering Properties

Due to the limited outcrop and the weathered nature of the Tertiary rocks in the study area no engineering characterisation of these lithologies has been attempted.

Geotechnical evaluation of the Elevation Mudstone (Brickell et al, 1976) suggests that due to rapid deterioration when exposed to the weather, this material is unsuitable for reclamation fill. The Shakespeare Bay Sandstone and Picton Conglomerate would probably compact readily, and perform reasonably well as fill.

2.3.4 Geological History

While little is known of the pre-Tertiary history of the older rocks in the study area, the presence of Tertiary sediments has provided some information on post Eocene tectonics. General subsidence during the Oligocene, possibly as a result of an extensional tectonic regime, allowed the accumulation of thick flysch-type deposits in an inner shelf or marginal marine environment. Nicol (1988) considered these may have been several kilometres thick, based on rank studies of coals near the base of the sequence. A change to an east-west compressional tectonic regime in the Miocene resulted in an eastward over-thrusting of schists over the Tertiary rocks, with associated development of north-south trending folds in the younger rocks. A change to south-east/ north-west compression resulted in a second phase of cross folding, which was in turn followed by a period of north-south trending strike slip faulting (Nicol, 1988).

The only evidence of Quaternary tectonic activity is associated with the Waikawa Fault, located to the east of Picton and Waikawa. A surface trace of this fault is visible running parallel to, and directly up slope from Moana View Road. Seismic deformation associated with movement related to this fault is observed in late Holocene gravels exposed in the Waikawa Stream (location WS2) Figure 3.2, map pocket) (see also sections 3.6).

2.4 SURFICIAL GEOLOGY

2.4.1 Regolith

For the purposes of this thesis regolith is defined as residual soil material formed in-situ as a result of weathering of underlying bedrock. With rare exceptions, regolith material is not preserved on the steeper slopes of the study area due to ongoing slope movements. It is restricted instead to the area of low relief along lower Waikawa Road, and to various other isolated gently sloping localities on the west side of Picton, and the eastern side of Waikawa.

Regolith material consists of deep yellow-red highly compact clays. Highly weathered litho-relics up to granule size are common. The regolith-bedrock interface is irregular and poorly defined, with a transition zone of typically 1 metre between residual soil and weathered bedrock. Organic topsoil development is limited to 100-200 mm in most cases, and a 150-300 mm white leeched zone (zone of eluviation) is often present at the top of the regolith profile (typical bedrock profiles are further discussed in section 3.3). Relict bedrock features, such as quartz/prehnite veins and argillaceous horizons are commonly preserved as colour changes only, the original textures being totally destroyed. Up to 1 metre of combined loess and slopewash deposits overly the regolith in some cases, and is inferred to have been deposited since the Last Glaciation.

2.4.2 Colluvium

Most steeper slopes in the study area (with the exception of very limited bedrock outcrops), are covered with a 1-2 metre veneer of colluvium. This material consists of moderately to highly weathered poorly sorted angular bedrock blocks ranging from small cobbles to 200 mm blocks set in a silty clay matrix (see Figure 2.1). The colluvium is matrix supported, and sharply overlies the bedrock surface. The contact is often controlled by discontinuous planar joints or fractures (see Figure 2.2).

Slopes over 20° generally support only a minimal thickness (0 to 1 metre) of blocky colluvium. The gentler foot slopes (5-20°) are overlain by predominantly fine grained colluvial matrix material washed down from the steeper terrain above.

2.4.3 Debris Flow Deposits

Near the head of Shakespeare Bay on the western side several large fans have developed out of steep catchments extending toward Mount Freeth (see Figures 2.3 and 2.4). Exposures at the shoreline show poorly sorted angular blocks of slightly to moderately weathered high grade schist set in a very well consolidated clay rich matrix. This material is matrix supported, and no imbrication or preferred orientation of schist blocks is observed. This suggests that these fans have developed as a result of a number of debris flow events. The term "debris avalanche" may be used

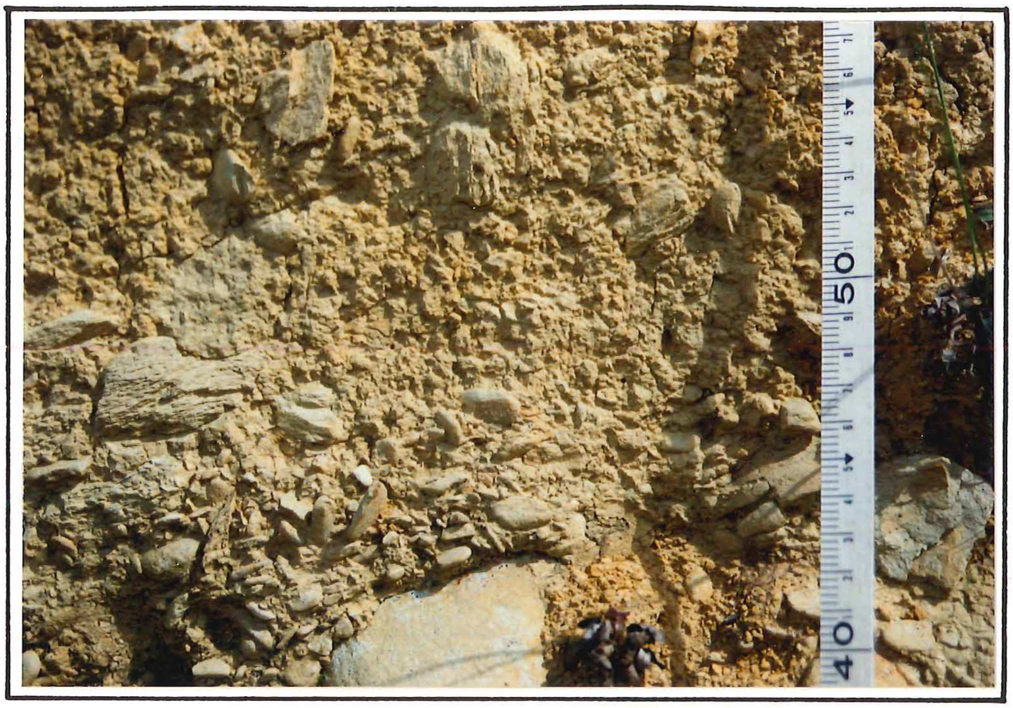


FIGURE 2.1. Greywacke colluvium; Poorly sorted angular blocks in a silty clay matrix.

FIGURE 2.2. Greywacke colluvium overlying joint controlled bedrock surface (location JS6; see figure 3.3, map pocket).

FIGURE 2.3. Large debris fan extending to the shoreline, western Shakespeare Bay.

FIGURE 2.4. Schist-derived debris flow deposits exposed at the shoreline of the Shakespeare Bay fan.

to describe such rapid debris flow events, although Varnes (1978) points out the possibility of confusion in using the term "avalanche" to describe mass movements in material other than snow and ice.

In contrast to the east Waikawa fans, fluvial processes appear to have had only a secondary role in post-depositional fan modification. The very steep nature of the contributing catchment areas may account for this higher energy mode of fan emplacement. As these fans aggrade to present sea level, they almost certainly post date the Otiran Glacial period, and the subsequent sea level rise.

2.4.4 Floodplain Alluvium

Extensive unconsolidated deposits of alluvial gravels are found at the heads of Picton Harbour and Waikawa Bay (see Figures 2.5 and 2.6). Gravel clasts are exclusively of Pelorus Group origin, ranging from granule size to 300-400 mm diameter boulders. Clasts are sub-rounded to rounded, and are typically slightly weathered, although highly to completely weathered gravels are found at locality WR2. The gravel matrix consists of sand and silt sized material, and there are wide variations in clast to matrix ratios. A weak to moderate clast imbrication is typically observed, and is more prominent in younger (Late Holocene) deposits. Occasional thin (up to 500 mm thick) beds containing only sand and silt are recognised (see Figure 2.6) , and yellow iron stained horizons indicate the previous positions of past water tables. While bedding is noted in both Waitohi and Waikawa Stream deposits, individual beds do not usually persist for more than a few metres. The discontinuous and often confused nature of the gravels is testament to the turbulence of the depositing streams (particularly the Waikawa Stream), which results in rapid channel migration, and episodic inundation of adjacent areas during flood events.

The older alluvial terraces are mantled with post glacial loess/slopewash deposits up to 1 metre thick (refer section 3.5), and estuarine muds and shells are incorporated in the gravel at the present shoreline.

2.4.5 Fan Alluvium

On the western side of Waikawa Bay a series of large, low angle (3-4°) alluvial fans have formed from stream catchments feeding the Waikawa

FIGURE 2.5. Imbricated moderate to fine alluvial gravels exposed in the stream bank, lower Waikawa Stream.

FIGURE 2.6. Coarse alluvial gravels with silt horizon underlying W_3 surface, Waikawa Stream.

Stream. The major period of fan formation was probably toward the end of the Otiran Glacial Stage, continuing into the Early Holocene (see section 3.5 for further discussion). Vegetation and soil profile development suggest that these fans are not presently active.

The deposits themselves are similar to terrace alluvium, although imbrication is less pronounced. The matrix appears to have a higher clay content than the terrace alluvium, which probably reflects the closer proximity of the source catchments. The rounded nature of the gravels and the presence of imbrication suggests deposition by migrating stream channels. Distinction is made between fans such as these which are deposited primarily by fluvial remobilisation of existing channel storage material, and the debris fans of western Shakespeare Bay, which appear to be a direct result of debris flows in the steep upper catchments. The Waikawa alluvial fans were probably deposited during a major Late Otiran-Early Holocene fluvial aggradation phase responsible for the W_1 terrace surface associated with the Waikawa Stream. Present day channels on these surfaces are incised, and show no sign of recent migration.

2.5 GEOMORPHIC EVOLUTION OF THE PICTON-WAIKAWA AREA

2.5.1 Tectonic Controls

The influence of tectonics and bedrock structure on geomorphic development is clearly visible in the study area. A general northwest-southeast alignment of major topographic features reflects the overall structural trend in the region with all major faults mapped having this orientation. Campbell and Johnson (1982) noted that valleys in the eastern Sounds align with bedrock schistosity. This observation is not valid for the majority of the study area, which is underlain by greywacke which has no significant schistosity development.

The depression occupied by Waikawa Road, Hampden Street and Milton Terrace (see Figure 2.9) is almost certainly the result of appreciable vertical displacement along the Waikawa Fault, which runs just below a series of facetted spurs behind Milton Terrace.

The low, flat topped hill comprising Victoria Domain (see Figure 2.9) has a considerably gentler relief than the other hills surrounding the study area, and exhibits a greater degree of bedrock weathering. While the significance of this is uncertain, it appears that this landform is considerably older than steeper hill slopes of the study area.

The absence of identified raised shore platforms suggests no net uplift during the Quaternary, in marked contrast to areas south of the Wairau River (Wellman, 1982). The deeply weathered nature of bedrock materials within the study area also suggests an absence of uplift and associated mechanical erosion.

2.5.2 Late Quaternary Climatic Controls

Climatic fluctuations throughout the Quaternary Period resulted in a series of glacial/interglacial climatic cycles. The cooler glacial intervals were characterised by considerable advances of the South Island glaciers, with corresponding changes in vegetation and fluctuations in sea level. Figures 2.7 and 2.8 summarise recent work concerning Quaternary sea level fluctuations.

While the Picton region was beyond the glacial ice limits (Lauder, 1987), the periglacial conditions which prevailed during these times resulted in a marked increase in mechanical erosion due to frost shattering, solifluction, and loss of the binding effect of vegetation.

No glacial outwash deposits are found in the Picton region, although gravels of the Speargrass Formation associated with the last glacial ice advance are found in the nearby Wairau and Kaituna Valleys (Beck, 1964). Extensive periglacial scree deposits have been described in the Sounds by Laffan (1980). While the poorly sorted, angular blocks found in the colluvial cover mantling the steeper slopes of the study area may have originated in a periglacial environment, the thick scree deposits described by Laffan (1980) are not observed. Kingsbury (1987), in a study of the Havelock/Linkwater region, tentatively identified periglacial deposits at only one locality.

The warmer, more humid interglacial intervals allowed the formation of deep weathering profiles (regolith) due to an increase in chemical weathering at the expense of mechanical erosion (see section 2.5.3). The extensive yellow/red regoliths observed throughout the study area were

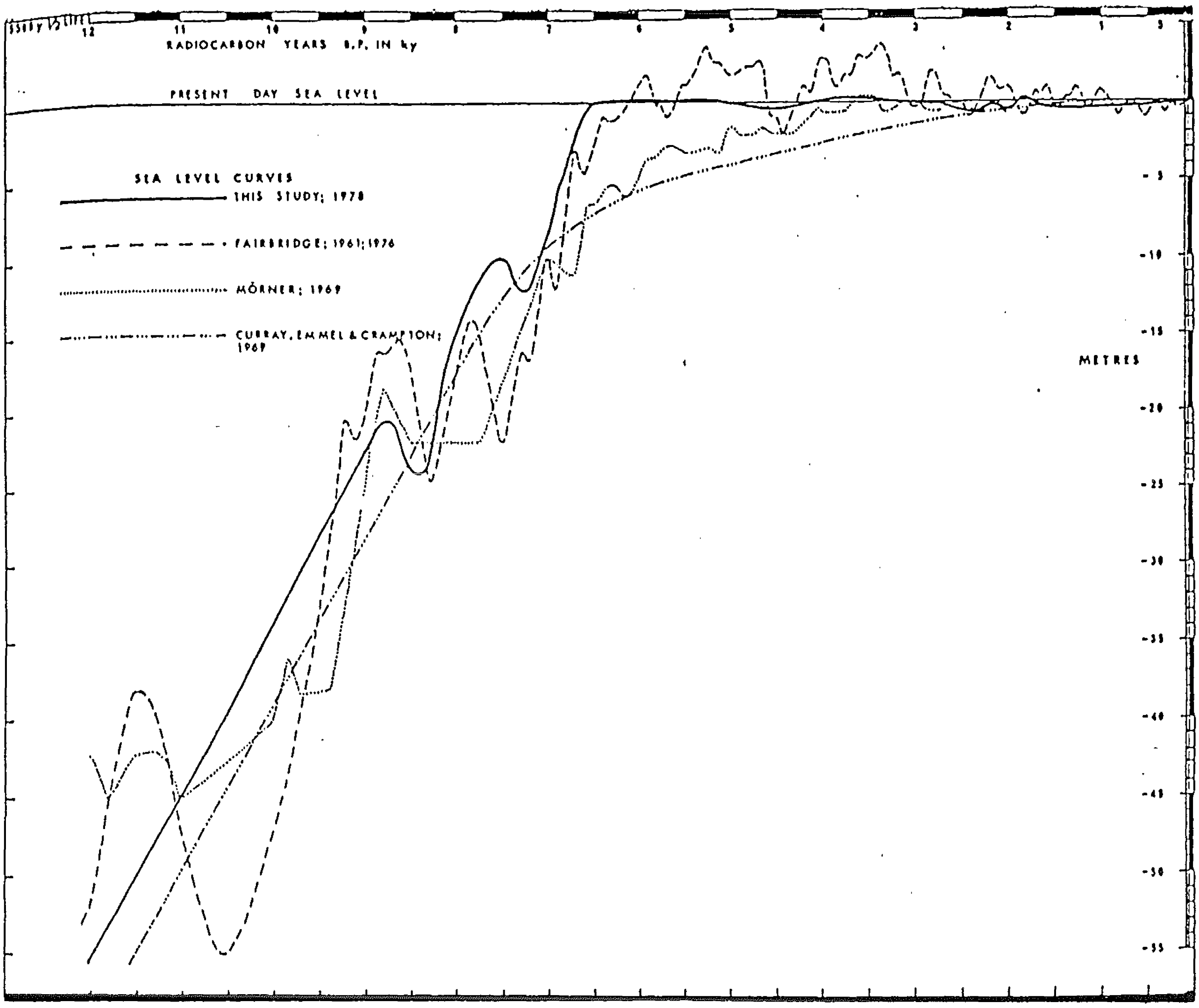


FIGURE 2.7. A summary of sea level curves indicating sea levels for the last 12 000 years. Diagram from Gibbs (1979).

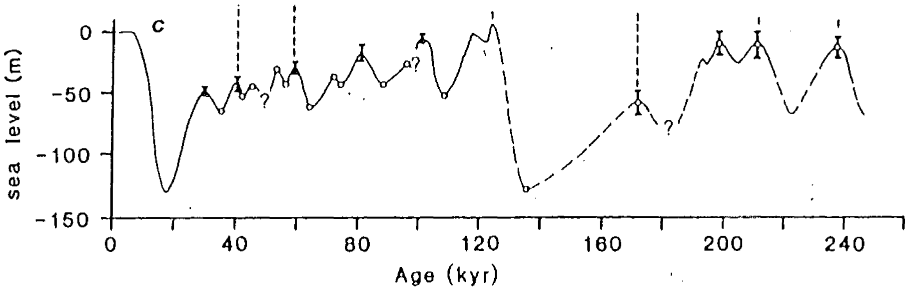


FIGURE 2.8. A summary of sea level fluctuation over the last 240 000 years. Diagram from Chappell and Shackleton (1986).

probably formed during these periods.

2.5.3 Weathering Processes

All bedrock lithologies within the study area are deeply weathered. It is thought that the majority of weathering took place during late Tertiary and Quaternary interglacial periods, when warm, humid climatic conditions prevailed. Intense chemical weathering during these periods resulted in the formation of extensive deposits of dark yellow-red regolith material (see Figure 2.10). Te Punga (1964), in describing similar deposits formed on greywacke bedrock in the Wellington region, concluded that the main red weathering episode was probably the Terangian Interglacial Stage. The Oturian Interglacial Stage is considered to be the last period of red weathering, constraining the age of such deposits to 120 000 years or older.

Red weathered regolith is observed in road cuttings on the Victoria Domain road in Picton (location V1), and along Boons Valley Road (location BV1) and Ranui Street (location RS1) at Waikawa. The red colour of the deposits is due to the presence of anhydrous haematite (Fe_2O_3), and is inferred from modern analogues to require an average temperature of 15.5°C and an average annual rainfall of greater that 1025 mm for formation (Te Punga, 1964). The present average temperature for the study area is 11° with an average rainfall of 1200 mm (Pascoe, 1983), which is unsuitable for the development of red weathered material.

Due to an active and varied tectonic history all bedrock materials within the study area are complexly and pervasively fractured. Iron rich waters infiltrating into the rock mass have resulted in dark brown iron staining on all fracture surface. This is particularly evident in Pelorus Group greywacke rocks, where even the tightest fractures are iron stained. Engineering geological investigation of the geotechnical characteristics of weathered bedrock material are further discussed in section 3.3

2.5.4 Slope Development

The valleys of the Sounds were formed by fluvial incision, resulting in a dendritic drainage system influenced by the northwest/southeast tectonic alignment of the region. The slopes surrounding the study area are

FIGURE 2.9. A view of the eastern arm of Picton township, looking nothwest. Note the subdued relief of the built up area, and Victoria Domain Hill (directly behind) compared with the surrounding hills (background). See text for discussion.

FIGURE 2.10. Late Otiran - Holocene loess and slope-wash deposits sharply overly a pre-Otiran red weathered bedrock surface, Ranui Street, Waikawa.

generally steep (slopes of up to 45° are common), and support only a 1-2 metre mantle of colluvial debris.

During the last glaciation the upper slopes would have been largely devoid of the thick vegetation cover that exists today. Accelerated mass wasting produced a considerable amount of debris which would have been transported out of the study area towards the contemporary coastline, somewhere in the vicinity of Cook Strait. It is likely that the few relict bedrock seated mass movement events identified in the study area were initiated during this time.

As climatic conditions warmed and vegetation became re-established on the tops, soils again began to develop through chemical weathering of bedrock. This fine clay rich material forms the matrix of the colluvial deposits observed today. Small scale mass movements (variable, but typically affecting 10-30 square metres) occur frequently in these deposits, resulting in the disturbed and poorly consolidated nature of the material. The bedrock/colluvium interface on the steeper slopes is sharp, and often controlled by joints or shears in the bedrock. This suggests periodic removal or disturbance of colluvium by slope movement. Almost all the mass movements occurring in the study area today may be classified as debris slide-flows, after the Varnes' (1978) classification scheme.

As very little bedrock outcrop remains, rock falls are almost non existent. The more gentle slopes underlain by bedrock have not been subject to the mass wasting characteristic of the steeper slopes, allowing the build up of deep in-situ regolith profiles.

2.5.5 Alluvial Deposition

Much of the lower catchments of Picton and Waikawa are underlain by coarse unconsolidated fluvial gravels deposited by the Waitohi and Waikawa Streams respectively. A smaller area of alluvial gravels also infills the head of Shakespeare Bay. In all catchments these gravels grade to the present day sea level.

A series of relict river terraces are noted as much as ten metres above the current active channels of both the Waitohi and Waikawa Streams, suggesting one or more periods of major fluvial aggradation. The alluvial deposits of the Waikawa stream are discussed in detail in section 3.5, and a model proposed to account for the formation of the various terrace surfaces.

2.6 SYNTHESIS

The study area is underlain by Pelorus Group greywackes and argillites in the east, and low grade Marlborough Schists in the West. A small area at the head of Shakespeare Bay is underlain by Tertiary marginal marine sedimentary rocks. 1-2 metres of bedrock colluvium covers the steeper slopes of the study area, while gentler bedrock surfaces are mantled by a greater thickness of regolith formed by in-situ bedrock weathering. Alluvial fan and floodplain deposits infill the lower catchments of Picton and Waikawa Bay.

The present day geomorphology of the study area is the result of a combination of cyclic climatic variations and tectonism. These factors have resulted in the weathering and fracturing of bedrock lithologies, increasing their susceptibility to mass wasting. The relatively consistent sea levels that have prevailed during Mid-Late Holocene times have allowed the formation of the extensive alluvial gravel surfaces in Picton and Waikawa Bay.

TABLE 2.1 LATE QUATERNARY HISTORY OF THE PICTON REGION

(Glacial Chronology after Suggate, 1965)

TERANGIAN INTERGLACIAL STAGE

- Major period of red weathering (Te Punga, 1963).
- Chemical weathering predominant.

WAIMEAN GLACIAL STAGE

- Low sea level, accelerated mass wasting.
- Period of aggradation resulting in formation W_0 surface (?).

OTURIAN INTERGLACIAL STAGE

- Chemical weathering predominant.
- Last red weathering episode (Te Punga, 1963)
- Sea level maximum similar to present level.

OTIRAN GLACIAL STAGE

- Sea level minimum 140 metres below present (Gibbs, 1979).
- Mechanical weathering, erosion and mass wasting predominant.
- Debris transported downstream, and out of study area.
- Initiation of several deep seated mass movements.

LATE OTIRAN GLACIAL - EARLY ARANUIAN INTERGLACIAL

- Major aggradation in study area to a rising sea levels.
- Deposition of gravels comprising W_1 surface.
- Deposition of East Waikawa alluvial fans. 6500 years B.P. Sea levels reach present day level plus or minus 1 metre (Gibbs, 1979).
- Commencement of deposition of Shakespeare Bay debris fan.

MID - LATE HOLOCENE

- Decrease in sediment supply due to re-vegetation results in nett degradation in lower Waikawa and Picton catchments.
- Formation of W_2, W_3, and W_4 surfaces.
- Tectonic disturbance and landform modification related to Waikawa Fault

HISTORICAL

- Deforestation by Polynesian and European burning resulted in a period of accelerated shallow colluvial slope movements.
- Formation of current active channel floodplain (W_5 surface) <100 years.
- The region remains seismically active.

CHAPTER 3

ENGINEERING GEOLOGICAL INVESTIGATIONS

3.1 INTRODUCTION AND OBJECTIVES.

The following chapter outlines the engineering geological investigations carried out for this project. The principal objective of these investigations has been to provide an engineering geological database for the Picton, Waikawa and Shakespeare Bay areas, such that it may be used as a basis for engineering geological hazard zonation, and for subsequent land use planning decisions. With this in mind, the specific investigation objectives were as follows.

(i) Regional engineering geological mapping of the whole study area at a scale of 1:10000, and detailed mapping of the Waikawa residential area at 1:5000.

(ii) Investigations of specific aspects of the engineering geology of the area, especially slope movements, bedrock weathering, alluvial deposition, and active faulting and seismicity.

Geotechnical investigations have been restricted to general characterisation of materials only, and detailed statistical analyses and inter-site correlations have not been attempted.

Following this introduction, the individual investigation methods are introduced (section 3.2). Investigation results are then discussed under the headings of bedrock weathering, slope instability, alluvial deposition, and faulting and seismicity (sections 3.3-3.6).

3.2 INVESTIGATION METHODOLOGY

3.2.1 Field Investigations

3.2.1.1 Engineering Geological Mapping

Engineering geological mapping of the whole study area at 1:10000, and of the Waikawa residential area only at 1:5000, forms the basis of the investigation programme for this thesis. The 1:10000 map was compiled primarily through air photograph analysis, using 1:10000 air photograph enlargements as a plotting base. Field checking of this map was limited by dense vegetation and accessibility problems, although all major features have been verified in the field. The primary purpose of the 1:10000 map is to indicate bedrock and surficial geology, together with some geomorphic information. As such, it is intended as a preliminary guide to expected foundation materials and conditions for use in land use planning.

The 1:5000 map of the Waikawa residential area was compiled along similar lines, although extensive field checking was undertaken, and additional geomorphic information has been included. This map is further discussed in the context of geological hazard assessment in section 4.5.3.

Due to limited exposure both these maps are to a certain extent interpretive, and are not intended as a substitute for proper engineering site investigations at individual section or subdivision scale.

3.2.1.2 Exposure Logging

Exposure logging constitutes a major part of the engineering geological investigation programme, providing a considerable amount of information on subsurface materials and conditions. The majority of exposure logging was confined to the Waikawa residential area, where ongoing urban development frequently provides fresh exposures in the form of road cuttings and foundation excavations.

In most cases the exposure was photographed, and descriptions made of all rock and soil units. Exposure logs were compiled at scales between 1:50 and 1:100. Bulk (disturbed) samples were taken where appropriate for later laboratory geotechnical analysis. Material and mass descriptions generally follow the schemes outlined by Bell and Pettinga (1983) (reproduced in Appendix 1).

3.2.1.3 Shallow Seismic Refraction Profiles

Shallow seismic refraction profiling using Soiltest Inc. single channel signal enhancement equipment was used to locate the bedrock surface for the Shakespeare Bay landslide and a section of the Waikawa Fault.

The arrival times of seismic waves refracted from the bedrock surface are recorded at various intervals along the seismic line. This data is then analysed by the reciprocal method (Hawkins, 1961) to give a continuous profile of the bedrock surface. The ground surface profile was surveyed using a Wild T1000 theodolite with electronic distance measuring equipment.

This technique proved to be a very useful way of determining depth to bedrock due to the excellent seismic velocity contrast between the colluvium (300 m/s) and bedrock (2000-4000 m/s). The main limitation in the use of this equipment is the hammer and plate energy source, which restricted the length of individual profiles to a maximum of 40 metres.

3.2.1.4 Hand Auger Holes

A series of seven 50 mm diameter hand auger holes were bored on the Shakespeare Bay site, and provided information on subsurface strata, groundwater levels, and depth to bedrock. Each hole was logged through the examination of cuttings, and some disturbed bulk samples obtained for water content, Atterberg limit and grainsize determination.

Auger holes were also useful in providing a direct control on seismic refraction profiles, in most cases verifying the accuracy of the seismic data. While the auger penetrates well (up to 5 metres) in fine grained foot-slope colluvium, some penetration problems were encountered with the blocky colluvium that covers the steep upper slopes.

3.2.1.5 Penetrometer Testing

A Scala penetrometer was employed to investigate bearing capacities in regolith profiles at locations WR3 and BV1 (see Figure 3.2, map pocket). A correlation exists between the penetration rate (e, expressed in mm/blow), and allowable bearing capacity (q_a, expressed in KPa). "Allowable" bearing capacity is defined as 3 times the "actual" bearing capacity, and thus incorporates a factor of safety of 3 (Kingsbury, 1987). While the penetrometer is a useful and convenient device for detecting changes in subsurface geology and depth to bedrock, its use in determining bearing capacities is restricted to fine grained homogeneous soils. As such it is not suitable for bearing capacity determination in the blocky slope colluvium and alluvial gravels comprising the foundation material throughout most of the Waikawa area.

3.2.2 Laboratory Investigations

3.2.2.1 Atterberg Limits

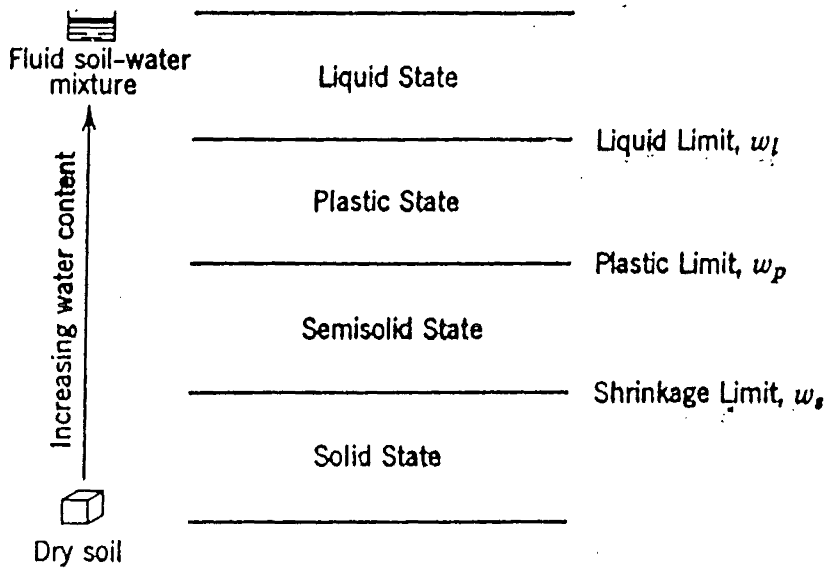
The behaviour of soil material depends largely on its water content, particle size distribution, and clay mineralogy. A particular soil may exist in four separate states, depending largely on water content (see Figure 3.6). The boundaries between these states are known as Atterberg limits, and are readily determined by simple laboratory tests. Atterberg limits are useful in the classification of a soil, and give an indication of the relationship between the behaviour of a soil under stress and water content.

In cohesive soils, soil behaviour is dictated by the silt and clay sized particles. Many of the samples collected contained larger particle sizes which tended to interfere with test procedures. For this reason it was decided to use only that material passing the 63 micron wet sieve for Atterberg determination, following the procedure outlined in NZS 4402 (1980). Atterberg limits for 11 samples of colluvial matrix and in-situ regolith material were determined.

Problems were encountered with the standard Casagrande dish method of liquid limit determination (NZS 4402, 1980). The samples tended to slide on the surface of the dish, instead of flowing as intended, thus invalidating the test. The Cone Penetration test (NZS 4402, 1980) was used as an alternative, and gave values for the Cone Penetration Limit (CPL), which may be considered equivalent to the liquid limit for CPL values less than 50.

3.2.2.2 Grain Size Analysis

Grain size distributions were determined for the same eleven samples



Plasticity Index:

$$I_p \quad \text{or} \quad PI = w_l - w_p$$

$$\left.\begin{array}{r}\text{Water-plasticity Ratio } B\\ \text{Liquidity Index } LI \text{ or } I_L\end{array}\right\} = \frac{w_n - w_p}{w_l - w_p}$$

w_n = natural water content

FIGURE 3.6. Definition of Atterberg Limits and related indices. Diagram from Lambe and Whitman (1975).

tested for Atterberg Limits. The samples were first treated with hydrogen peroxide to remove organic material, then passed through a 63 micron wet sieve to separate the sand and mud fractions.

The sand fraction was analysed by sieving through 1, 0.5, 0.25, 0.125, and 0.0625 mm (0,1,2,3, and 4 phi) dry sieves. The mud fraction was analysed by the hydrometer settling column method. Test procedures follow those outlined in NZS 4402 (1980).

3.2.2.3 X-Ray Diffraction Identification of Clay Minerals

X-Ray Diffraction identification of clay minerals was carried out for samples of both colluvial matrix and greywacke regolith. Clay mineralogy influences the behaviour of a soil as some clay minerals (chiefly those of the smectite group) absorb water readily, with a corresponding change in volume. The presence of these minerals in a soil mass can have a negative influence on slope stability. Orientated mounts were prepared by evaporating a small volume of clay suspension obtained from the settling columns used in grain size determination. The three-fold method of clay mineral analysis employed follows that of Hutchison (1974), and is outlined below.

(i) The orientated slides were run to identify the diffraction peaks associated with the (001) surfaces of the clay minerals present.

(ii) Each slide was then impregnated with ethylene glycol and run through the diffractometer again. This has the effect of expanding the basal spacings of minerals of the montmorillonite group (swelling clays), thus readily differentiating peaks associated with these minerals from those of non-swelling clay minerals.

(iii) Finally, each slide was heated to 500°C for approximately 1 hour. Heating drives off water from certain minerals, causing their structure to collapse and removing the associated diffractogram peaks.

Clay mineral identification through x-ray diffraction is a highly specialised technique, and ideally requires further data from differential thermal analysis. The aim of this study is to identify the principal clay mineral groups present, rather than attempting any detailed study of clay composition.

3.2.2.4 Rock Strength Testing

Laboratory rock strength testing of ten suites of weathered bedrock samples was undertaken, using both the point load test (ISRM, 1984) and the NCB cone indenter test (MRDE, 1977). These tests were also used to investigate rock strength in low grade schist terrain at Havelock by Kingsbury (1987).

The point load test involves applying an increasing point load to a rock sample until failure occurs. Given the failure load, and the sample size parameters, the point load strength index may be calculated. This value has been shown empirically to correlate with unconfined compressive strength (ISRM, 1984) , which can therefore be calculated for the sample. The test is repeated a number of times, and average values obtained. Although originally intended for testing rock cores, this test may be applied to irregularly shaped samples using the irregular lump test procedure, as outlined by Brock and Franklin (1972). The procedure for analysis of results is detailed by ISRM (1984).

The NCB cone indenter test was applied to the same ten samples tested for point load strength. Test procedure followed that outlined by MRDE (1977). This test involves indentation of the surface of a fresh rock chip by a hardened steel cone of specified dimensions under a constant load. The depth of indentation is then measured, and a cone indenter number calculated for the sample. Once again, a correlation exists between cone indenter number and unconfined compressive strength, which may then be calculated for the sample.

3.3 GEOTECHNICAL CHARACTERISATION OF WEATHERED BEDROCK

3.3.1 Introduction and Objectives

Weathered bedrock constitutes the foundation material for the majority of the study area. It exists either in the form of in-situ regolith (see section 2.4.1), or transported colluvium (see section 2.4.2). The objective of this study is to characterise the properties of weathered greywacke bedrock for the Picton-Waikawa area. It is intended that this work, in conjunction with engineering geological mapping, will provide an indication of expected foundation conditions for residential development. Detailed geotechnical characterisation of individual weathering grades (as undertaken by Kingsbury, 1987) is considered beyond the scope of this project.

This section begins with a case study of the Jeffcott subdivision site at Waikawa, and goes on to briefly discuss several other sites that were investigated and sampled. This is followed by a summary and discussion of the data obtained through field and laboratory testing, and presentation of principal conclusions.

3.3.2 Jeffcott Subdivision Case Study

The Jeffcott Subdivision site lies just north of the Waikawa Bay store, and encompasses approximately 0.6 square kilometres of steep weathered greywacke slopes (see Figure 3.7). The subdivision, which was commenced in late 1987, represents the first major residential development on the steep slopes surrounding Waikawa, and as such is of special interest from both engineering and planning points of view. The performance of this subdivision may have a significant effect on the guidelines and restrictions placed on other residential development projects in similar steep terrain.

The subdivision access road is cut into slopes of 20-30° and provides excellent subsurface exposure to depths of 5 - 6 metres. The principal objective of this case study was to investigate the geotechnical properties of weathering profiles characteristic of this type of terrain.

A data summary sheet including exposure logs, sample locations, a cross section and an engineering geological plan is included in the map pocket (Figure 3.3). This figure presents a number of weathering profile logs, and an engineering geological plan (1:1250) which covers the subdivision site and Amelia and Authur Crescent areas directly to the south. The subsurface geology of the site is relatively uniform, and consists of 1 to 2 metres of blocky greywacke colluvium overlying in-situ bedrock. Typically the top 1.5 to 2 metres of bedrock is highly weathered (Grade IV), followed by a 0.5 metre transition zone to moderately weathered

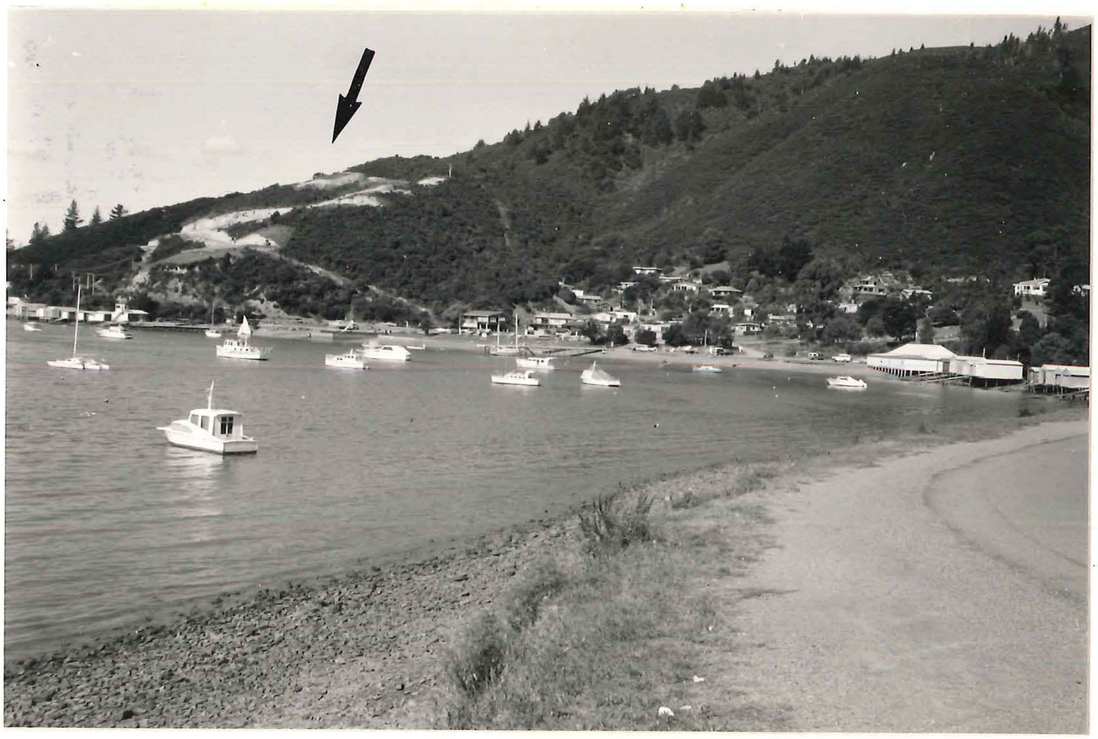


FIGURE 3.7. A view of eastern Waikawa Bay showing the Jeffcott subdivision (arrowed).

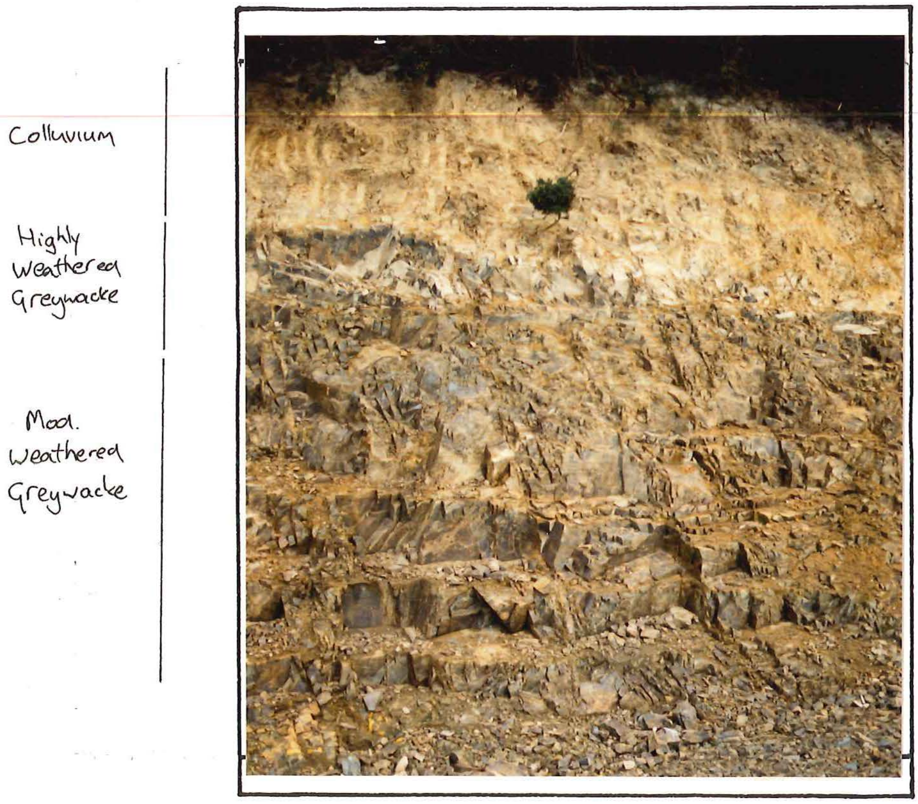


FIGURE 3.8. Typical bedrock weathering profile exposed in the access road, Jeffcott subdivision. 1.5 metres of blocky colluvium overlies moderately to highly weathered jointed greywacke bedrock.

bedrock (Grade III). Slightly weathered bedrock (grade II) is only observed in deeply incised stream gullies.

In all cases bedrock is highly fractured, containing both regular joint sets, and random, non-planar fractures. Several well developed low angle shear zones were observed in the road cutting and in some cases these extended for several tens of metres, consisting of 10 -20 cm wide zones of crushed rock. Some seepage was noted from within these shear zones, suggesting they could form potential bedrock failure planes in cases where shear zones dip gently downslope

The bedrock/colluvium interface is sharply defined, and is often controlled by low angle discontinuity surfaces (see Figure 2.4). This, coupled with the existence of buried organic material in stream profiles, suggests periodic mobilization of colluvium by slope movement. A number of small colluvial failures have also occurred below the main Port Underwood road, where road works and coastal erosion have over-steepened the foreshore area.

Relict landslide features are noted in natural ground on the west side of Amelia Crescent (see Figure 3.3). The slopes to the east of Amelia and Authur Crescents show extensive signs of instability, the most recent being a debris slide-flow event during the early 1980s. Although accessibility to these slopes is restricted by dense scrub, a number of other re-vegetated landslide scars are visible. Although this area is not a part of the Jeffcott subdivision, it is included on the engineering geological plan presented in Figure 3.3.

Building sites within the Jeffcott subdivision have been restricted to the ridge tops, which present the least problems in terms of slope instability. The access road, however, traverses side-slopes, and is likely to be subject to small scale (areal extend less than 10 metres) discontinuity controlled batter failure and rock fall, requiring periodic maintenance.

The results of geotechnical testing of samples from the Jeffcott subdivision site are discussed in section 3.3.4.

3.3.3 Other Sites

In addition to the Jeffcott subdivision, samples of weathered bedrock material were collected from a number of other sites throughout the Waikawa Residential Area. The location of each of these sites is shown in Figure 3.2 (1:5000 engineering geological map of Waikawa, map pocket), and associated exposure logs are presented in Appendix 4.

From this information, and observations in the Picton catchment, a series of typical weathering profiles for various geomorphic settings are presented in Figure 3.11. Deere and Patton (1971), in a detailed review of bedrock weathering profiles in relation to slope stability, proposed a weathering profile model for metamorphic rocks. This was slightly modified by Kingsbury (1987), and applied to weathering profiles in low grade schist in the Havelock area of the Marlborough Sounds (see Figure 3.9). This model also appears to be generally applicable to greywacke weathering profiles in the Picton area. Figure 3.10 illustrates the relationship between this model and the weathering grade classification of Bell and Pettinga (1983), which has been used in this study.

3.3.4 Data Summary

3.3.4.1 Soil Material

The results of Atterberg limit determinations and grain size analyses for all residual soil and colluvial matrix samples tested are summarised in Table 3.1. Liquid limit values range from 25 to 40 (average 32), plastic limits from 17 to 29 (average 23), and plasticity indices from 3 to 14 (average 10). These results are in close agreement with average index properties for residual greywacke soils from the Wellington region (Liquid limit: 30, plasticity index: 10), determined by Pender (1971). Each sample is plotted on a standard Casagrande plasticity chart in Figure 3.12. The plotted data points straddle the "A" line, classifying the samples as either silts or clays of low to moderate plasticity (using the USCS scheme, see Appendix 1).

It is noted that in most cases natural water content values are close to liquid limit values. Given that sampling was carried out in dry conditions, it is likely that natural moisture content would exceed the

Deere and Patton (1971)	Kingsbury (1987)
	A Colluvium
I Residual Soil	B Regolith
IA Horizon (Eluviation)	Ba Horizon (Eluviation)
IB Horizon (Illuviation)	Bb Horizon (Illuviation)
IC Horizon (Saprolite)	Bc Horizon (Saprolite)
II Weathered Rock	C Weathered Rock
IIA Horizon (Transition Zone)	Ca Horizon (Transition Zone)
IIB Horizon (Partly Weathered)	Cb Horizon (Partly Weathered)
III Unweathered Rock	D Unweathered Rock

FIGURE 3.9. Weathering profile models proposed by Deere and Patton (1971) and Kingsbury (1987).Diagram from Kingsbury (1987).

Weathering Grade	Profile Model Horizon
VI Residual Soil	A Colluvium Ba Eluviation Bb Illuviation
V Completely Weathered	Bc Saprolite
IV Highly Weathered	Ca Transition Zone
III Moderately Weathered II Slightly Weathered	Cb Partly Weathered
I Unweatherd	D Unweathered

FIGURE 3.10. Correlation between weathering grade classificaton (Bell and Pettinga, 1983) and weathering profile model (Kingsbury, 1987).

TABLE 3.1. SUMMARY OF INDEX PROPERTIES FOR RESIDUAL GREYWACKE SOILS.

SAMPLE	LOCATION	DEPTH	TYPE*	CPL	r	PL	PI	ACTIVITY	GRAVEL	SAND	SILT	CLAY	ϕr **	UCS SYMBOL	W_n ***
R1	BV1	2m	R	40	.97	29	11	.42	5%	46%	25%	26%	16	ML	29
R2	BV1	1m	R	40	.85	24	16	.46	2%	21%	42%	35%	13.5	ML	21
R3	WR3	2m	R	40	.99	29	11	1.10	10%	35%	45%	10%	16	ML	38
R4	WR3	1m	R	46	.93	32	14	.37	6%	27%	29%	38%	14	ML	-
R5	QC1	1.9m	R	30	.97	21	9	.24	-	27%	36%	37%	17.5	Cl	-
M2	WM1	0.7m	C	32	.96	25	7	.27	11%	16%	47%	26%	19.3	ML	20
C2	JS6	0.6m	C	29	.99	20	9	.39	5%	17%	55%	23%	17.5	CL	-
C5	PR1	1.85m	C	25	.99	17	8	.44	4%	20%	58%	18%	18.5	CL	-
J8	JS4	0.25m	C	29	.85	18	11	.61	9%	39%	34%	18%	16	ML	18.6
J9	JS5	0.5m	C	24	.96	21	3	.27	16%	37%	36%	11%	28.5	ML	13.4
C6	SB1	1.5m	C	27	.94	18	9	.39	-	15%	62%	23%	17.5	ML	22.4

* R denotes in-situ residual soil, C denotes colluvial matrix material.

** Calculated using formula of Kanji, 1974 (see text)

*** Natural water content (weight percent).

Refer to figures 3.2 and 3.3 for sample localities.

TABLE 3.2. ROCK STRENGTH TESTING RESULTS.

SAMPLE	LOCATION	WEATHERING GRD.	SAMPLE DEPTH	LITHOLOGY	POINT LOAD TEST			NCB CONE INDENTER TEST		
					No.of tests	$I_s(50)$	UCS (MPa)	No.of tests	I_m/I_s*	UCS (MPa)
J1	JS2	IV	1.9m	sandstone	0	--	--	10	I_m=0.93	23.2
J2	JS2	III	3.8m	sandstone	22	0.42	10.2	10	I_m=1.85	66.28
J4	JS3	III	4.9m	sandstone	12	0.18	4.21	10	I_s=4.76	118.16
J5	JS3	III	2.1m	sandstone	11	0.20	4.79	10	I_m=2.70	96.72
J6	JS4	IV	1.0m	sandstone	11	0.36	7.58	10	I_s=1.55	38.45
J7	JS4	III	4.4m	sandstone	10	0.14	3.41	12	I_s=3.85	95.54
J10	JS5	IV	1.9m	sandstone	**Too weak to test**					
J11	JS5	III	3.9m	sandstone	---	----	--	10	I_s=2.05	50.76
M1	WM1	III	5.0m	mudstone	Parallel to bedding:					
					3	0.19	4.52	--	----	--
					Normal to bedding:					
					10	0.62	14.86	10	I_s=3.46	85.83
M3	WM1	III	5.0m	sandstone	10	0.11	2.53	10	I_m=2.40	85.83

* I_s =standard cone indenter number. I_m= modified cone indenter number (see MRDE 1977)

Refer to figures 3.2 and 3.3 (map pocket) for sample localities.

liquid limit during periods of prolonged or intense rainfall, with a corresponding marked decrease in the shear strength of the soil. This clearly contributes to the susceptibility of weathered bedrock material to slope movements.

The plasticity index (liquid limit - plastic limit) is the range of water contents for which the soil exists in the plastic state (see Figure 3.6). The plasticity index depends on the proportion of clay sized material present, and the clay mineralogy of the soil. By dividing the plastic limit by the percentage clay content, the clay content variable is removed. The value thus derived provides a relative measurement of the plasticity of the soil, and is dependent only on clay mineralogy. This value is known as the activity index of the soil.

Activity data for the major clay mineral groups (from Skempton, 1953) is presented in Figure 3.13. Similar work on weathered schist bedrock from the Havelock area (Kingsbury, 1987) is also shown. The average activity index for the 10 completely weathered bedrock samples tested for this study is 0.45 (Standard deviation 0.23). This result is very close to the empirically derived value for kaolinite (Skempton, 1953), which has been identified by x-ray diffraction as the principal clay mineral component in these samples. Lesser amounts of quartz and chlorite were detected in all samples tested, while traces of montmorillonite group minerals were detected in some samples. It is noted that activity values for this study are considerably less than those of Kingsbury (1987). This is presumably due to a greater proportion of active clay minerals in weathered schist compared with weathered greywacke. This would be expected given the presence of a significant proportion of micas in weathered low grade schist, whereas kaolinite is the principle weathering product of the predominantly quartzofeldspathic greywackes of Pelorus Group.

Experimental work by Kanji (1974) has shown that a reasonable correlation exists between the plasticity index (I_p), and the residual angle of internal friction for a soil (Ør). The following expression quantifies this relationship:

$$Ør = 46.6 / I_p^{\,0.446}$$

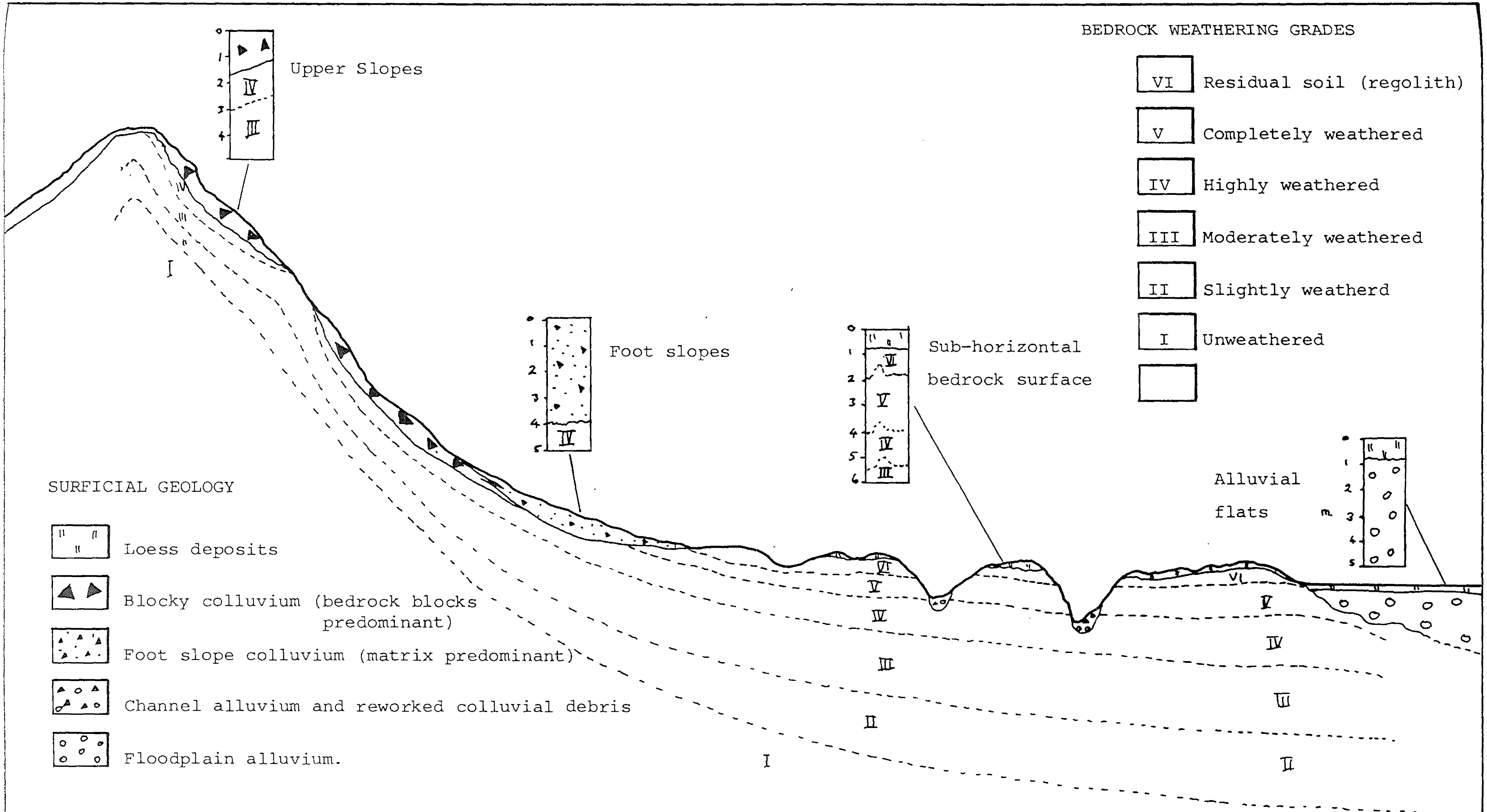


FIGURE 3.11. Schematic cross section showing typical weathering profiles for various types of terrain in the Picton-Waikawa area. The vertical scale is exaggerated

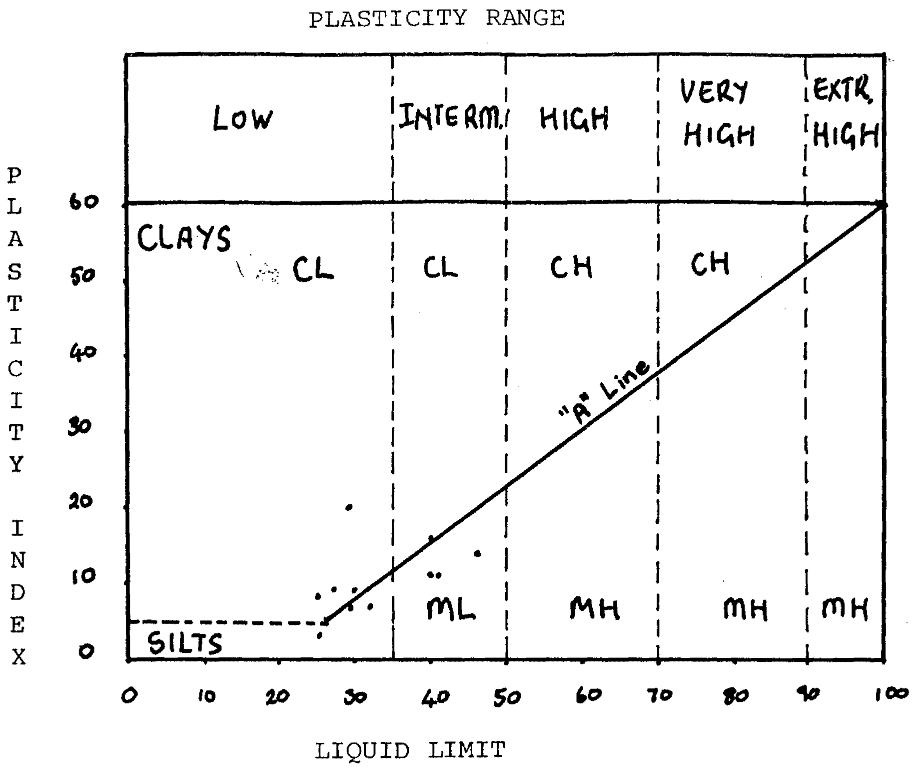


FIGURE 3.12. The distribution of plasticity values for weathered greywacke regolith shown on a Casagrande plasticity diagram.

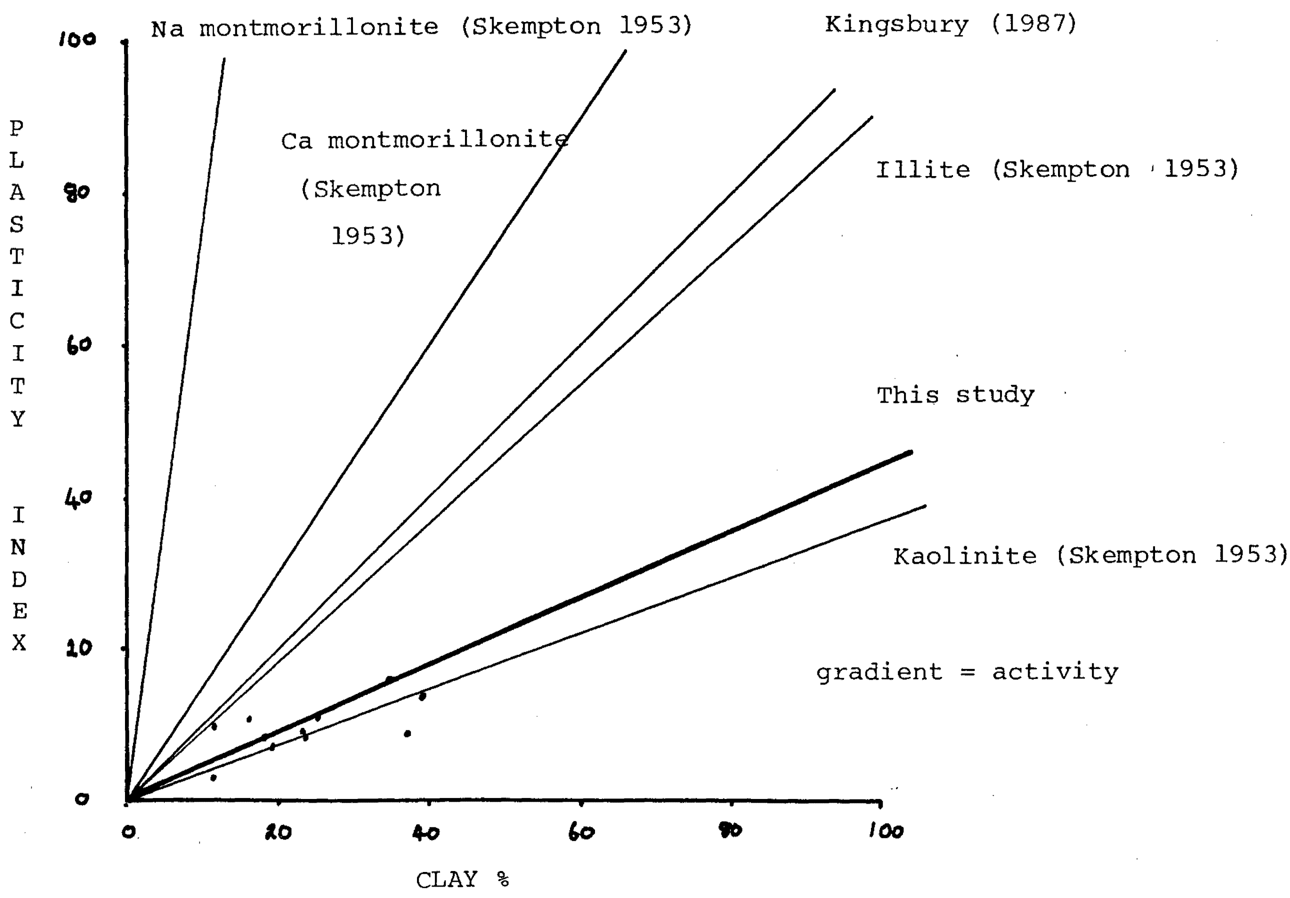
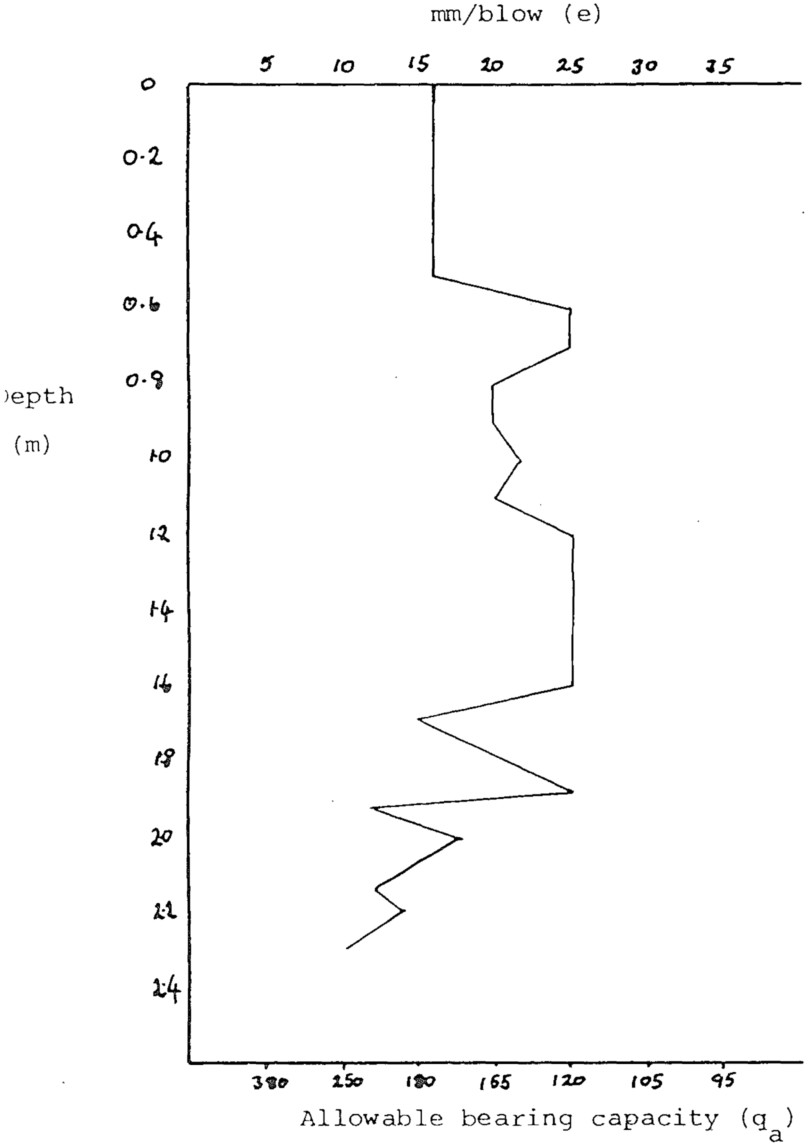


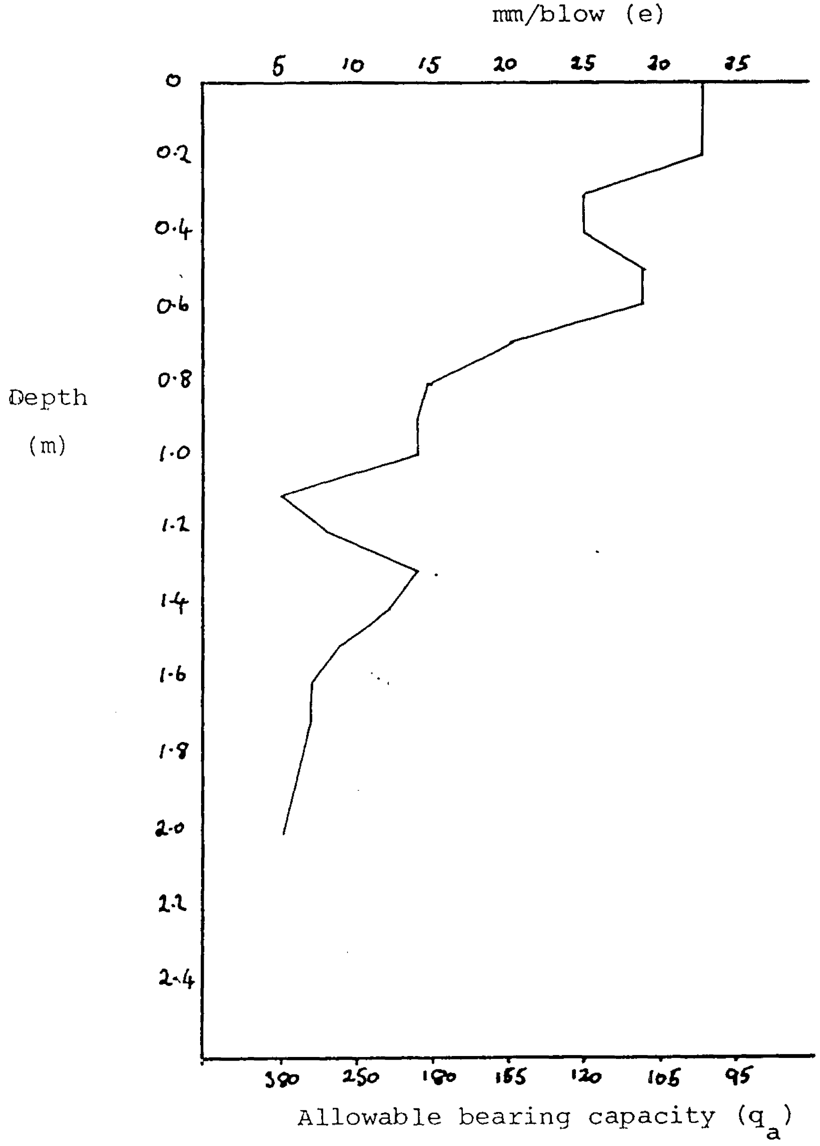
FIGURE 3.13. Activity data for weathered greywacke regolith compared with results from Kingsbury (1987) for similar work in weathered schist, and experimental data from Skempton (1959)

FIGURE 3.14. BEARING CAPACITY DATA FOR GREYWACKE REGOLITH DETERMINED FROM PENETROMETER TESTING.

LOCATION WR3, Waikawa Road (see figure 3.2, map pocket)



LOCATION BV1, Boons Valley Road.'(see figure 3.2)



The application of this equation to I_p values for the samples tested for this study indicates a range of Ør values of between 14 and 18° for weathered greywacke soils. Kanji (1974) also summarised various attempts to correlate I_p values with the peak angle of internal friction, (Ø´), but concluded that this relationship has still to be reliably quantified.

Penetrometer testing provided an indication of the bearing capacity of completely weathered regolith material at locations WR3 and BV1. Allowable bearing capacities (q_a) for the soil are plotted against depth below ground surface for these localities in Figure 3.14. In all cases q_a values are well in excess of 100kPa, the minimum recommended for residential structure without special foundation design (NZS 3604).

3.3.4.2 Rock Material

Rock material strength testing using both cone indenter (MRDE, 1977) and point load (ISRM, 1984) test methods to determine rock strength index values for weathered greywacke bedrock (grades III and IV). The results of this testing are summarised in table 3.2. Computed values of unconfined shear strength using the point load method are considerably lower than those obtained by the NCB cone indenter test. This discrepancy is due to fundamental differences between these methods, as outlined below.

The point load test (see section 3.2.2.4) gives a direct measurement of rock strength, which in the case of the weathered greywacke samples tested, is greatly influenced by fractures in the rock. An estimated 90% of all point load tests carried out resulted in failure along existing fracture surfaces. The relatively weak nature of the samples tested caused problems with fracturing around the platens prior to failure. Further error is introduced by the inherent inaccuracies in estimating the average diameter of highly angular and irregularly shaped samples.

The NCB cone indenter test (see section 3.2.2.4) measures rock hardness, which is then correlated with rock strength. This technique clearly assumes that discontinuities do not significantly reduce the strength of the rock. The considerably higher unconfined compressive strength figures obtained from this test are thought to represent theoretical values for greywacke with no significant rock defects. As such, these do not give an accurate measure of actual rock mass strength for the weathered greywacke of the study area.

Although results of the above tests show a general increase in rock strength with a decrease in weathering grade, rather more data is required to quantify this relationship. Ideally, a large number of samples should be tested by the point load method, with samples being of equivalent shape and size.

3.3.5 Conclusions

The following principal conclusions are drawn from the above studies: (i) The Jeffcott subdivision is located on steep but relatively stable weathered bedrock slopes. The typical weathering profile consists of 1 to 2 metres of blocky greywacke colluvium sharply overlying highly weathered but in-situ bedrock. Moderately weathered bedrock is encountered 1.5 to 2 metres below the bedrock surface.

(ii) Greywacke bedrock underlying the steeper slopes is pervasively jointed and fractured, and a number of relatively persistent (tens of metres) shear zones were noted.

(iii) The building sites in the subdivision appear to be located on relatively stable ridge top situations. Extensive signs of instability are however observed on the slopes to the east of Amelia and Authur Crescents, and development of this area is not recommended without further detailed investigation.

(iv) Low angle bedrock surfaces (the lower Waikawa Road area) are typically underlain by a considerably thicker weathering profile formed predominantly by in-situ weathering. Residual soils of 1 to 2 metres thickness overly completely weathered greywacke. Lack of suitable exposure makes it difficult to develop a weathering profile model below this depth. Up to 1 metre of post-glacial loess/slopewash deposits often overlies residual soil.

(v) Geotechnical characterisation of greywacke regolith and colluvial matrix using Atterberg limits, x-ray diffraction, and grainsize analysis can provide an indication of expected soil behaviour. In general, all samples tested may be classified as inactive silts or clays of low to moderate plasticity. Detailed investigation of strength parameters for these materials would require extensive tri-axial and/or shear box testing. This information would, however, be useful in the design of retaining walls and foundations.

(vi) Rock strength determination using both point load and cone indenter testing is of limited use for the weathered greywackes of the study area due to the high number of closely spaced irregular fractures in the rock mass. While the results of each test may be useful as relative indices of rock strength, it is felt that correlation with unconfined compressive strength values is unreliable in this case.

3.4 SLOPE MOVEMENT MODELS

3.4.1 Introduction and Objectives

The following section aims to develop engineering geological models for the major classes of slope movement (i.e. failures in bedrock, colluvium, and cut slopes) observed in the study area. Models for failure of bedrock and colluvium in natural ground are primarily based on investigations of unstable slopes in Shakespeare Bay, although reference is made to other sites in the Waikawa area. A model for failure of cut batters is also discussed with reference to examples at the Waikawa Marina.

3.4.2 Shakespeare Bay Case Study

The cleared slopes directly west of the old freezing works site in Shakespeare Bay show considerable evidence of instability, and were chosen for specific study because:

(i) The slopes are relatively clear and accessible.

(ii) A number of mass movement processes are evident.

(iii) Port Marlborough New Zealand Limited has extensive plans for the development of the Bay as a port facility.

A study of the area was made based on:

(i) Compilation of an engineering geological map of the area (1:1000) showing bedrock and surficial geology, and mass movement features.

(ii) Investigation of subsurface conditions by shallow seismic refraction, hand auguring and limited geotechnical testing.

(iii) Development of engineering geological models for slope movements in both colluvium and bedrock.

The upper slopes are steep (30-45°) and consist of low grade moderately weathered mica schist mantled by 0 to 1 metre of blocky schist colluvium. Tertiary mudstone underlies the lower slope, and is covered by 2 to 5 metres of silty clay footslope colluvium. The schist and mudstone are inferred by regional geological mapping to be in fault contact (Nicol, 1988)

A large bedrock seated landslide is observed toward the western end of the slope, while a number of more recent shallow colluvial failures are evident across the whole area. Active removal of the toe of the slope is ongoing due to wave and tidal action at the shoreline. Man-made disturbance of the area is limited to the south-eastern corner, where several waste treatment buildings and access tracks were constructed in the 1960's.

Engineering geological mapping was carried out at a scale of 1:1000 based on aerial photograph interpretation and field surveys (see Figure 3.4, map pocket). This map was compiled on a 1:1000 topographical base plan provided by the Marlborough Harbour Board. Exposures in road cuttings and landslide scarps were examined to determine the distribution of surface deposits. Seven 50 mm diameter hand auger holes provided further subsurface information, and shallow seismic refraction profiling proved a successful technique in locating the bedrock-colluvium interface. One sample of colluvial matrix clay (SB 1) was retained for determination of Atterberg limits and grainsize distribution, and a number of samples were retained for moisture content determination.

3.4.3 Bedrock Seated Slope Movement Model

The large landslide on the western end of the Shakespeare Bay slopes has a well defined headscarp extending approximately 5 metres into bedrock, and has produced a large debris lobe extending to the shore. The age of this event is not known, but historical photographs suggest it is pre-European.

Close examination of the weathered schist bedrock exposed at the headscarp reveals several prominent closely spaced joint sets. Observations of outcrops suggest these joints dictate the behaviour of the rock mass, and suggest that the landslide occurred as a multiple wedge failure, with both release and down-slope movement taking place along joint controlled surfaces. Failure initiation was probably a result of high cleft water pressures in open joints in the headscarp region during or soon after a period of high rainfall. In this case, removal of toe support by wave action is also identified as a contributing factor. Given that the Picton area is seismically active, it is also possible that the landslide may have been triggered by an earthquake.

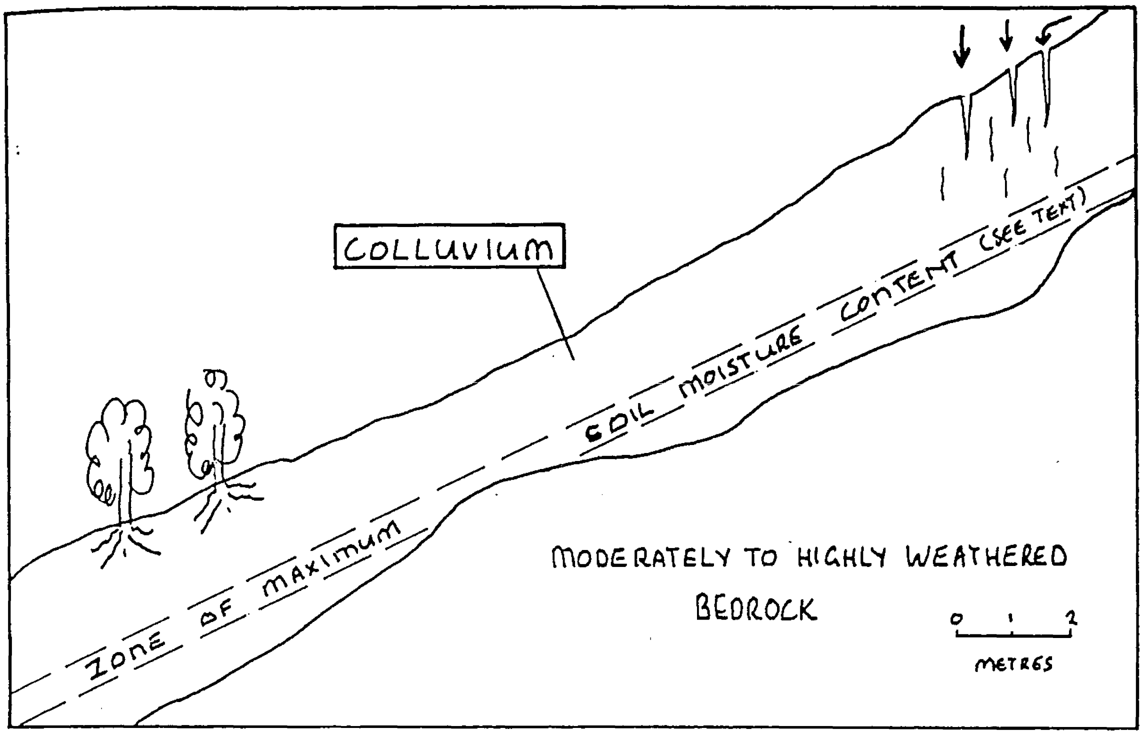
Although the Shakespeare Bay site is underlain by low grade schist, this material appears to have geotechnical properties similar to those of the weathered greywacke underlying Picton and Waikawa. While bedrock-seated failures in natural ground are rare, several such features have been identified in the Waikawa area, and are thought to be related to a period of accelerated slope movement associated with the last Glacial Stage. No modern examples are observed, although these relict features are liable to smaller scale secondary re-activation.

3.4.4 Colluvium Seated Slope Movement Model

A number of shallow colluvial failures have occurred on the Shakespeare Bay slopes, the largest and most recent being located directly below a cut track adjacent to the waste treatment buildings, and extending to the shoreline (see Figure 3.15). Such failures are also common on the hills surrounding Picton and Waikawa, particularly in areas where natural slope drainage has been disturbed by road or track construction.

FIGURE 3.15. Landsliding in colluvium, eastern Shakespeare Bay.

A. Run-off infiltration occurs through dessication and tension cracks in the headscarp region. Soil moisture is greatest in a 0.5-1 m zone between 2 and 3 metres below the ground surface.



B. Falure occurs along a failure surface within the zone of maximum moisture content during a period of heavy rainfall. The bedrock surface constitutes the failure surface only where it intesects this zone.

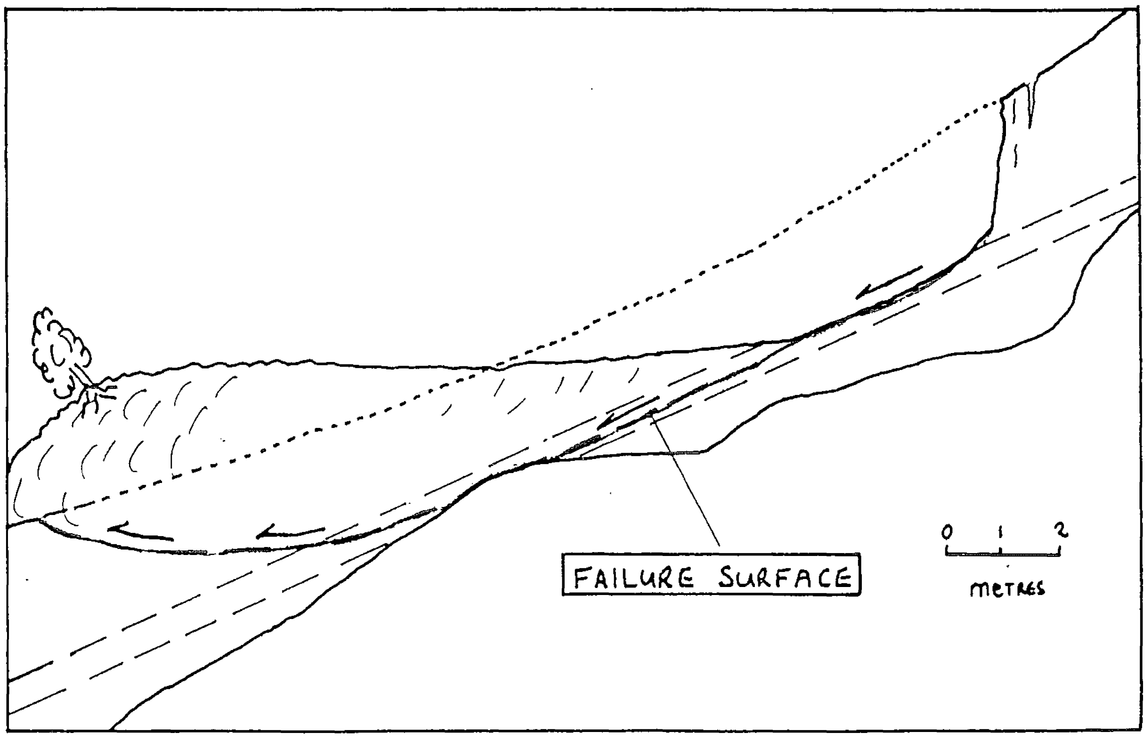


FIGURE 3.16. 2 stage diagram illustrating the failure model for landslides in colluvium. See text for further explaination.

Colluvial failures are due to excessive buildup of pore water in the soil mass, and as such are directly related to sustained or intense rainfall episodes. The fine grained nature of the colluvial matrix (55-75% silt size or smaller) results in poor internal drainage, promoting a rapid buildup of water pressure where tension or desiccation cracks allow water infiltration.

The failure surface is usually no more than 2 to 3 metres below the surface. A series of natural moisture content samples collected from auger hole No. 7 (see Figure 3.5, map pocket) indicate a soil moisture content close to the materials liquid limit at this depth (W_L= 24%, W_n = 20%). Below 3 metres a rapid decrease in moisture content was noted, suggesting that the majority of surface infiltration is retained in the top 2 to 3 metres of colluvium. Where the colluvial cover does not attain this thickness failure usually occurs at the bedrock surface.

The dense vegetation covering much of the study area has a significant "binding" effect on slope colluvium. Many landslide events in the area may be attributed to prior removal of vegetation. In addition to the stabilizing effect of roots, vegetation also intercepts and controls run-off, and reduces soil moisture by evapo-transpiration. Shallow slope movements are further discussed in chapter 4 in the context of geological hazards.

3.4.5. Cut Batter Failure Model

Road batter failure has been a problem where roads are cut into steep (20-30°) weathered greywacke slopes. Problems have been experienced along the Port Underwood road north of Waikawa, and at the Waikawa marina (see Figures 3.19 and 3.20). As residential development extends on to steeper terrain, further batter instability may be expected.

Failure in bedrock cut slopes is strongly influenced by the nature and orientation of rock mass defects. The greywacke bedrock of the study area contains many joints and fractures, and is highly susceptible to wedge failure along unfavourably orientated planes of weakness. The uppermost 2 to 3 metres of bedrock generally contains many closely spaced (1-5cm) defects with a wide range of orientations. Below this depth there is a gradual reduction in defect density, and distinct sets of similarly

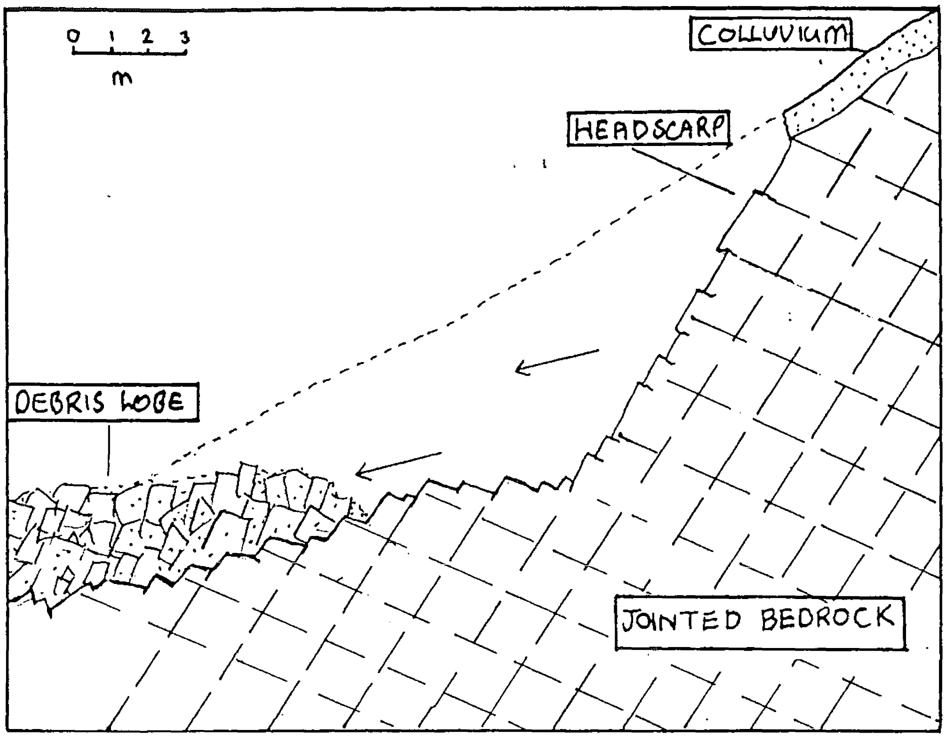


FIGURE 3.17 Cross sectional sketch illustrating multiple wedge failure model for bedrock seated landslides.

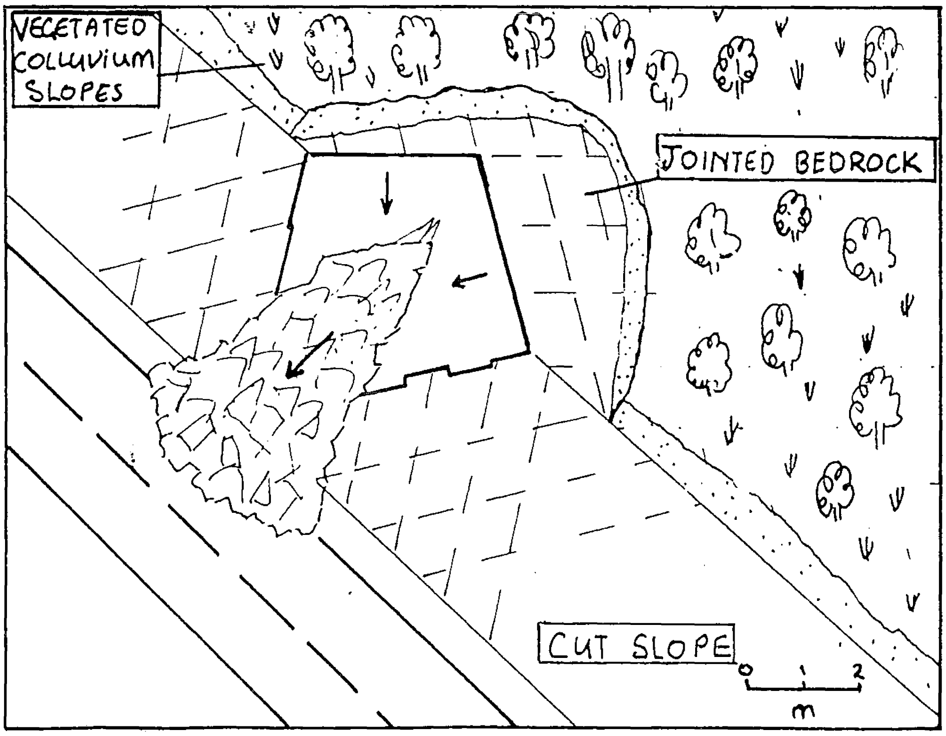


FIGURE 3.18. Oblique sketch showing joint controled wedge failure model for batter instability in weathered greywacke cut slopes.

orientated defects are more easily recognised. For this reason batter failures in the top 2 to 3 metres tend to involve many small defect controlled blocks (i.e. multiple wedge failures), while deeper failures involve a lesser number of larger blocks.

A number of bedrock wedge failures have occurred in the road cutting on the western side of the Waikawa marina (location WM2, see Figure 3.19). A relatively large bedding plane failure has occurred at location WM1 (see Figure 3.2, map pocket). In this case the strike of bedding was within 20° of the trend of the cutting, and was dipping at approximately 20° less than the batter angle.

In these cases failure is initiated either by initial excavation, or by a build up of crack water pressure during heavy rainfall. Seepage was observed in a number of bedrock cuttings, where joints and fractures provide a path for groundwater flow. While some of these failures occur along regular defect surfaces, it is not thought feasible to predict rock mass behaviour through rock defect surveys and standard stability analysis procedures. The large number of rock defects and the wide range of orientations makes it very difficult to identify the most probable failure planes in weathered greywacke material.

3.4.6 Conclusions.

There are no recorded historical examples of large scale bedrock seated landslides in the study area. A number of such events have occurred in the past, however, and in some cases these are subject to limited secondary re-activation. Bedrock seated landslides are controlled by one or more of the many rock defect sets common in both low grade schist and greywacke bedrock. Other factors that may contribute to failure are sustained high rainfall, toe removal by fluvial or coastal erosion, and the occurrence of seismic events.

Shallow landslides in colluvium are common throughout the study area, and are a direct result of high intensity or long duration rainfall. Such failures are usually restricted to the top 2-3 metres of colluvium due to the low permeability of the silty clay colluvial matrix.

FIGURE 3.19. Bedding plane failure in cut batter, Waikawa Marina (location WM1, see figure 3.2, map pocket).

FIGURE 3.20. Joint controlled wedge failure in road batter, Waikawa Marina.

Failures in cut batters are also common in the area, and are controlled by planar bedrock defects. Such failures are often caused or aggravated by poor site drainage following excavation.

3.5 ALLUVIAL DEPOSITION.

3.5.1 Introduction and Objectives

Much of the urban development in the Picton and Waikawa area has taken place on extensive flats formed by deposition of alluvial gravels derived from the steep upper catchments. An understanding of the fluvial processes periodically active in the area is fundamental to the identification and assessment of associated geological hazards of flooding, debris deposition, and stream bank erosion (discussed in chapter 4). The objective of the following section is to develop an engineering geological model for the formation and subsequent modification of these surfaces, based on investigation of the Waikawa Stream alluvial terraces.

3.5.2 Waikawa Stream Alluvial Deposits

A series of 6 alluvial terrace formed by the Waikawa Stream (W_0-W_5) have been mapped (see Figure 3.2). Individual surfaces have been differentiated on the basis of relative elevation.

Coarse alluvial gravels are observed in a road cutting on Waikawa Road (see Figure 3.21). This cutting is approximately ten metres above the present Waikawa Stream bed and exposes two gravel units differing markedly in degree of weathering. The unit furthest away from the Waikawa Stream (W_0, exposed at location WR2), is completely weathered and exhibits red weathering, which is indicative of an age older than the last (Oturian) interglacial (Te Punga, 1964) (see section 2.5.3 for further discussion of red weathering). The unit closer to the Waikawa Stream (W_1, exposed at location WR1), contains slightly to moderately weathered clasts similar to present day stream alluvium. On this basis the W_1 gravels are constrained to an age younger than the Oturian interglacial. The elevation of this outcrop suggests that both W_0 and W_1 gravels were deposited during major periods of Waikawa Stream

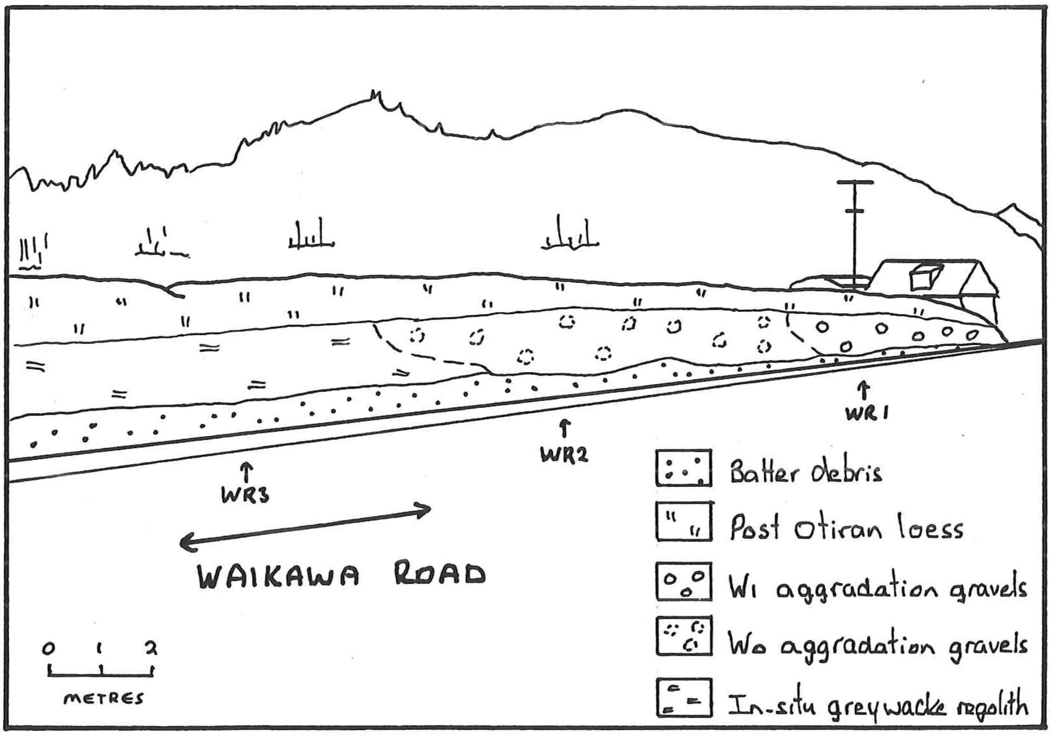


FIGURE 3.21. W_1 and W_0 aggradation gravels exposed at location WR, Waikawa Road. See figure 3.2 (map pocket) for location.

FIGURE 3.22. Completely weathered alluvial gravels of the W_0 aggradation phase exposed at location WR2, Waikawa Road (see figure 3.2, map pocket, for location).

FIGURE 3.23. Slightly to moderately weathered alluvial gravels of the W_1 aggradation phase exposed at location WR1, Waikawa Road (see figure 3.2, map pocket, for location).

aggradation, when sediment supply would have been considerably greater than the present.

Since deposition of the W_1 surface, successive downcutting of the Waikawa Stream has occurred, resulting in the formation of a flight of four terrace surfaces decreasing in elevation and age toward the present channel position. This downcutting is most noticeable in the upper catchment areas (upstream of the Waikawa Road bridge), where W_1 gravels are found as much as 10 metres above the present level of the active channel. Below the bridge there is evidence of only minimal stream incision. A steady decrease in clast size in progressively younger gravel deposits also suggests a reduction in the volume of material produced by mass wasting and re-mobilisation of fluvial debris in the upper catchments.

A net West to East migration of the Waikawa Stream accounts for the fact that the W_2 and W_3 surfaces are only preserved on the western side of the present active channel (see Figure 3.2, map pocket). The discontinuous and disturbed nature of alluvial gravel deposits exposed in the banks of the active channel suggests that the majority of deposition has occurred during turbulent flood events. Historical records and discussions with local residents indicate that the Waikawa Stream is prone to flooding and debris deposition during intense rainfall, although little quantitative data is available.

Several large alluvial debris fans have built out from series of catchments on the east side of Waikawa (see also section 2.4.5.). These fans appear to interfinger with W_1 gravels, and were probably formed during the same aggradation phase. Smaller scale, younger alluvial debris fans have formed from a number of other catchments in the area, either building out onto older alluvial surfaces, or aggrading to present sea level. A detailed exposure log of a section through a small debris fan developed on the W_4 surface is included in Appendix 5. Two samples of buried wood have been collected from this exposure approximately 2 metres beneath the W_4 surface for Carbon 14 dating. These dates should provide some absolute age control on the age relationships of the various alluvial surfaces in the lower Waikawa Stream. Due to unforeseen delays these dates were not available in time to be included in this thesis.

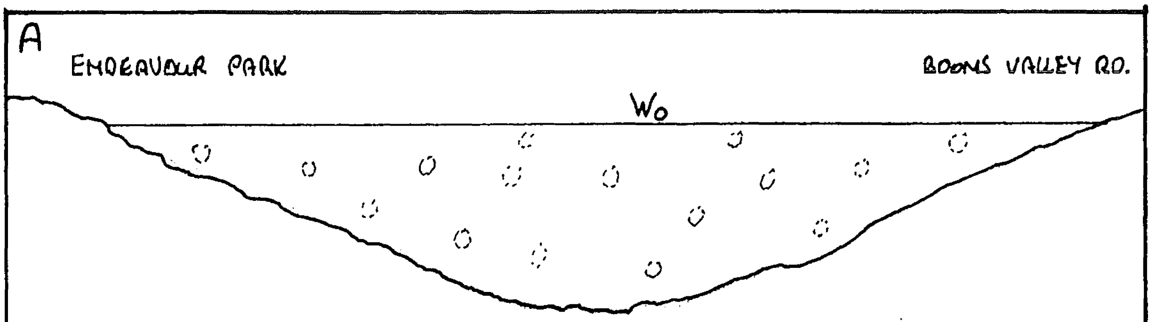
3.5.3 Alluvial Deposition Model

All Waikawa Stream alluvial surfaces aggrade more or less to the present day sea level. Assuming that the sea level during the Otiran glacial reached a minimum of 140 metres below the present (Chappell and Shackleton, 1986), any alluvial material generated within the catchments of the study area would have been rapidly transported toward the contemporary coastline somewhere in the Cook Strait area. It is therefore assumed that no significant alluvial deposition occurred during low sea level stands. Any alluvial material deposited during earlier (i.e. Pre-Otiran) high sea level stands would have been severely eroded due to channel downcutting and associated net degradation in response to lowering sea levels.

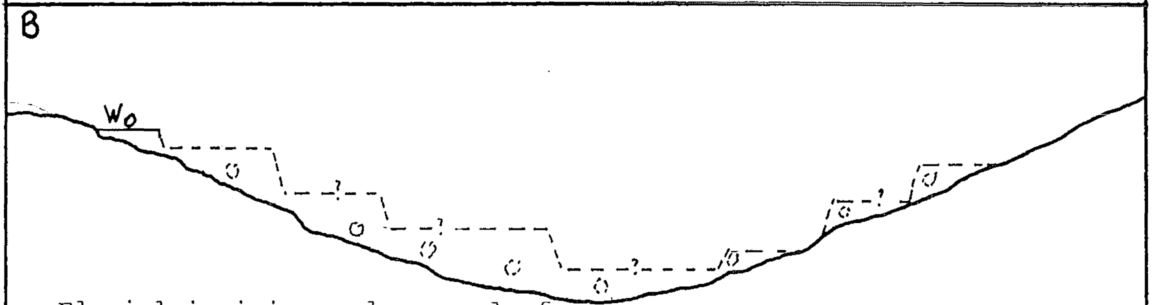
The major alluvial aggradation phases represented by the W_1 surface (and possibly the W_0 surface) would require a sediment supply considerably greater than at present. The periglacial environment prevailing during glacial times would provide this through increased erosion and reduced vegetation on upper slopes. It therefore appears that some compromise between sea level and sediment supply is required to account for these aggradation events.

The composite sea level curve presented by Gibbs (1979) (see Figure 2.7) indicates a steady rise between 10000 years ago to 6500 years ago, when sea levels attained approximately their present position. Suggate (1965) indicated that the major retreat of the South Island glaciers around 14000 years ago marked the end of the Otiran glacial. There is, however, evidence of glacial advances subsequent to this, suggesting that periglacial conditions may have persisted in the study area up to about 10000 years B.P. (Burrows et al, 1976).

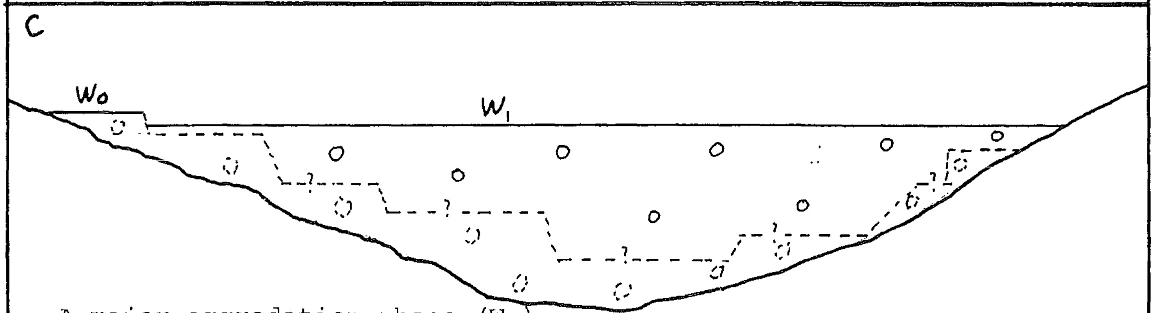
It seems most likely that the W_1 surface was formed between 10000 and 6500 years B.P. Alluvial material derived from accelerated mass wasting in the steep upper catchments was transported downstream, and deposited in response to a rising sea level. The gradual decrease in fluvial incision toward the shoreline suggests a progressive decrease in channel gradient as a result of rising sea level coupled with a decrease of sediment supply. The W_2, W_3 and W_4 surfaces represent intermediate stages of terrace formation between W_1 aggradation and the present situation.



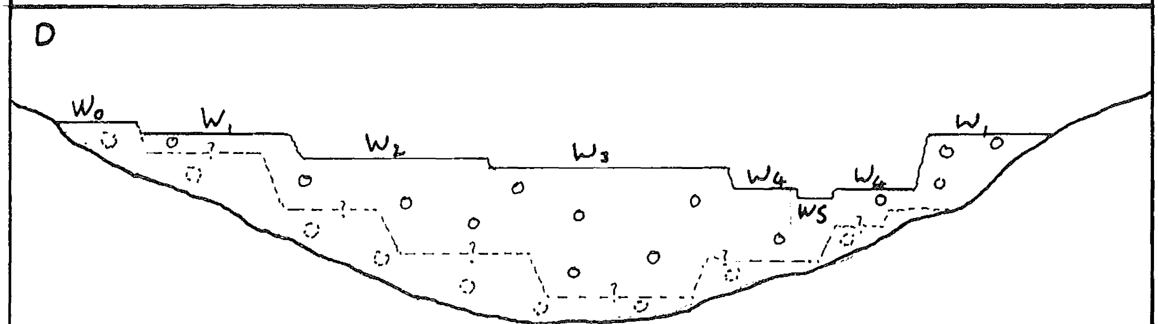
A major pre-Otiran aggradation phase fills the lower Waikawa Stream catchment with alluvial gravels (late Waimean-early Oturian ?)



Fluvial incision and removal of alluvial gravels (late Oturian - Otiran). Further aggradation events probably occured during the Otiran Glacial, but are not preserved.



A major aggradation phase (W_1) infills the lower catchment with alluvial gravels almost to the level attained by W_0 aggradation (late Otiran-early Aranuian).



Fluvial incision and removal of alluvium during the Holocene result in the formation of W_2, W_3 and W_4 surfaces.

FIGURE 3.24. Schematic cross sections outlining the Late Quaternary development of the Waikawa Stream alluvial surfaces. Sections are normal to river flow direction, looking seaward.

The proposed sequence of development of the Waikawa Stream alluvial complex detailed in Figure 3.24.

While no direct age control is available, it is likely that the W_0 surface is a remnant of an earlier (pre-Otiran) aggradation phase of the Waikawa Stream. Only the restricted area of this surface lying beyond the limits of W_1 activity is preserved.

3.5.4 Conclusions

The majority of the alluvial floodplain gravels in both the Picton and Waikawa catchments were probably deposited during a major aggradation event commencing in the periglacial conditions of the late Otiran Glacial, and continuing until present sea levels were attained around 6500 years B.P. A series of major alluvial fans formed from stream catchments to the east of the Waikawa residential area are also attributed to the event. Since that time gradual fluvial incision has left a succession of elevated river terraces.

A small remnant of completely weathered gravels exposed in Waikawa Road is thought to date from an earlier fluvial aggradation phase, which is tentatively correlated with the Late Waimean-Early Oturian Stages on the basis of observed red weathering.

While quantitative data on catchment hydrology for the study area is lacking, both the historical and geological records indicate that flooding and related hazards pose a potential threat to urban development in the Waikawa area.

3.6 FAULTING AND SEISMICITY.

3.6.1. Introduction and Objectives

The Marlborough Sounds area is seismically active due to its proximity to the Australian-Pacific plate boundary. A number of major faults have been mapped in the study area (Beck, 1964, and Nicol, 1988), and are shown in Figure 3.1 (map pocket). While most of these faults exhibit no evidence of Quaternary activity, a surface trace of the Waikawa Fault has been identified on the eastern side of the Waikawa residential area. The following section outlines the results of investigations of this fault trace, together with estimates of its activity.

3.6.2 Waikawa Fault Trace

A surface trace of the Waikawa Fault trending at approximately 045-050° is observed on bedrock hill-slopes on the eastern side of the Waikawa residential area. Further south the fault manifests itself as a series of facetted bedrock spurs, running parallel to and just east of Milton Terrace (see Figure 3.1, map pocket). No surface expression of the fault is observed beyond the south end of Milton Terrace, although it is inferred to continue southward along the range front, passing through the low saddle at The Elevation.

The nature and sense of movement of the fault is difficult to determine due to the poor preservation of the surface trace. The rapid change in slope 200 metres up slope from Milton Terrace, combined with the presence of facetted spurs, suggests appreciable vertical displacement, with the eastern side being upthrown. Vertical offset in the same sense is noted at location MV1 (see Figure 3.2, map pocket), just east of Moana View road at Waikawa. The Waikawa Stream changes course by almost 90° where it crosses the inferred position of the fault, and the courses of several smaller streams further north also appear to be disturbed. On the basis of these apparent stream offsets a right lateral sense of horizontal displacement is proposed.

A shallow seismic refraction profile was run across the fault trace along the Cemetery Road in an effort to locate the exact position of the Fault and to investigate the nature of any bedrock offset. A reasonably consistent refractor was found, and was inferred to represent the bedrock surface. This refractor showed no appreciable vertical offset, and on the basis of this it was decided that trenching across the fault trace was not warranted at this locality.

3.6.3 Activity of the Waikawa Fault.

The Waikawa Fault traverses Late Holocene alluvial terraces formed by the Waikawa Stream. Although no surface trace of the Fault is observed on

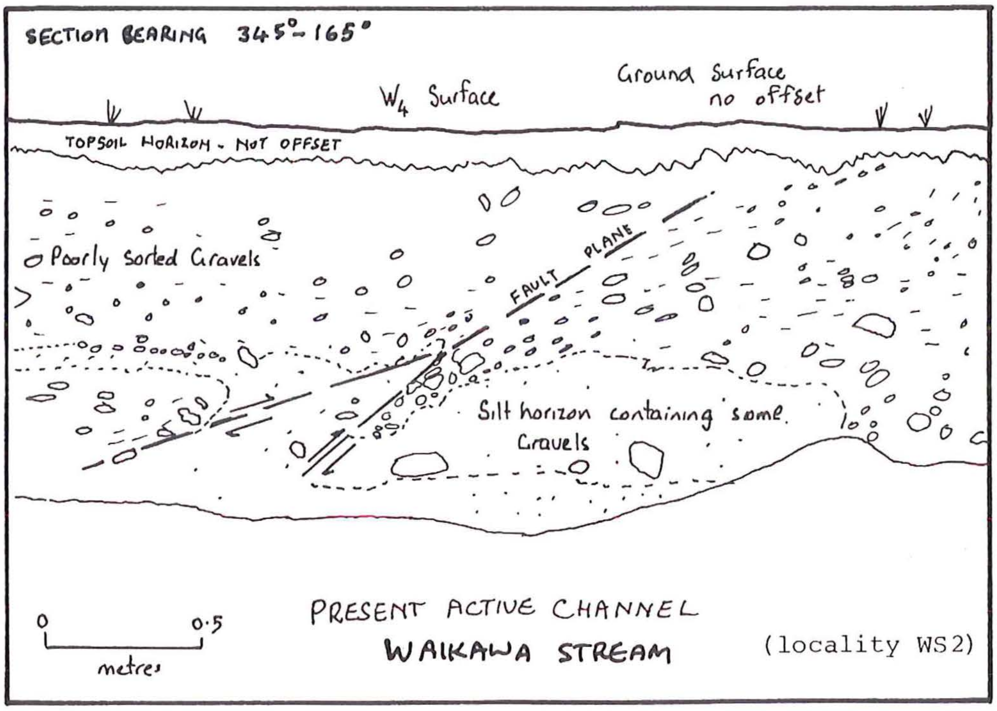


FIGURE 3.25. Small scale faults observed in Late Holocene alluvial gravels, Waikawa Stream (W_4 surface). This locality is within 100 metres of the inferred position of the Waikawa Fault.

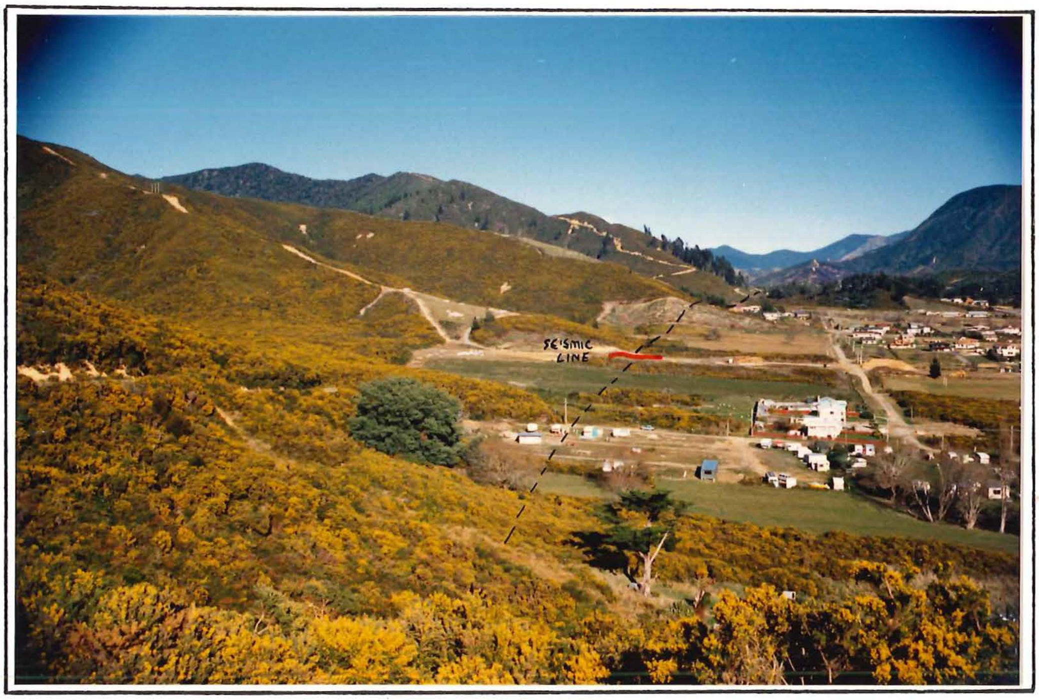


FIGURE 3.26. Eastern Waikawa residential area, showing the degraded trace of the Waikawa Fault.

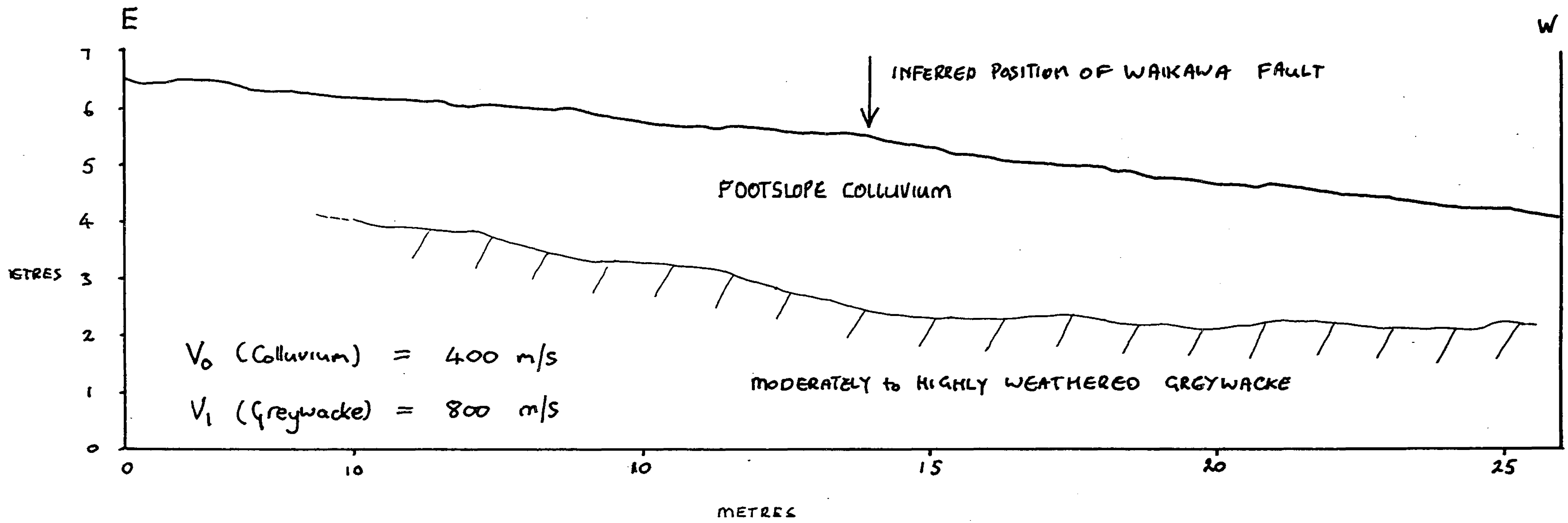


FIGURE 3.27. Shallow seimic refraction profile across the inferred position of the Waikawa Fault, Cemetary Road, Waikawa. The location of the profile is shown in figure 3.26.

		Movement in last 5000 years		
		Repeated	Single	None
Movement in 5,000-50,000 years	Repeated	I	I	II
	Single	I	II	III
	None	I	III	-
Movement in 50,000-500,000 years	Repeated	I	II	III
	Single	I	III	Not active*
	None	I	III	-

* May be mapped as "Late Quaternary Fault Trace" (see below).

The above table implies the following definitions:

A Class I Active Fault is principally one that has shown repeated movement over the last 5,000 years, but the category also includes those with a single movement then and repeated movement in the last 50,000 years.

A Class II Active Fault is considered less active than one in Class I. It is principally one that has shown, as a minimum, repeated movement over the last 50,000 years, but the category also includes those with a single movement in the last 5,000 years and repeated movement in the period of 50,000 to 500,000 years ago.

A Class III Active Fault is the least active of those faults that are expected to move again. It is principally one that has shown, as a minimum, a single movement in the last 50,000 years, but also includes those showing repeated movements in the period of 50,000 to 500,000 years ago.

FIGURE 3.28. The New Zealand Geological Survey active fault classification scheme. Diagram from NZGS (1966).

these terraces, a series of small scale faults are noted in the stream bank nearby, at location WS2 (see Figure 3.2). Three small reverse faults are observed at this exposure, each having approximately 0.5 metres of vertical offset along fault planes with apparent dips of between 30 and 50° to the south-east (see Figure 3.25). These faults continue to within 0.3 metres of the ground surface. These features are probably the result of ground deformation due to seismic activity associated the Waikawa Fault. Little information on fault activity can be gained from investigation of the fault trace where it crosses bedrock slopes due to highly variable rates of landscape modification by slope movements

The tectonic disturbance of gravels of late Holocene age indicates at least one event associated with the Waikawa Fault Zone within the last 5000 years, based on the disturbance of Late Holocene gravels. The Waikawa Fault may therefore be assigned a class III activity rating, after the New Zealand Geological Survey's Active Fault Classification Scheme (N.Z.G.S, 1966, see Figure 3.28). It is highly likely that there has been single or repeated fault movements between 5000 and 50000 years ago, but lack of definitive evidence precludes a higher activity classification.

3.6.4 Conclusions.

Ground deformation associated with seismic activity along the Waikawa Fault zone has occurred in late Holocene times. The fault trace itself is extensively masked by subsequent alluvial and slope movement deposits, and does not appear to offset Holocene floodplain gravels. From the limited surface expression it is difficult to determine the sense of fault movement, although the presence of facetted spurs directly east of Milton terrace suggests significant uplift on the eastern side of the fault, and stream offsets infer a right lateral sense of horizontal displacement. The fault is assigned a class III activity rating on the basis of disturbance of Late Holocene alluvial terraces.

3.7 SYNTHESIS

This chapter outlines the findings of the engineering geological investigations carried out for this thesis. Laboratory geotechnical testing characterised greywacke regolith and colluvium samples on the basis of grainsize distribution, Atterberg limits, and clay mineralogy. The samples tested were either silts or clays of low to medium plasticity, with an average activity index of 0.45, and kaolinite as the principle clay mineral component. Rock strength testing of moderately to highly weathered greywacke rock samples by point load and cone indenter methods yielded a wide range of results, and it is concluded that the results of these tests are best used as independent relative indices of rock strength.

Typical bedrock weathering profiles for various geotechnical settings have been developed on the basis of investigations at the Jeffcott subdivision, and throughout the Waikawa area. Slope movement failure models for landslides in bedrock, colluvium and cut slopes are proposed on the basis of investigations at eastern Shakespeare Bay and the Waikawa marina. The alluvial deposits of the Waikawa Stream are almost exclusively Late Otiran to Early Holocene in age. Mid-Late Holocene fluvial incision has resulted in the formation of a flight of degradation terraces, on which much of the Waikawa residential area is situated. An Late Quaternary trace of the Waikawa Fault is preserved on the eastern side of Waikawa, and this has been active in the last 5000 years. This information, in conjunction with engineering geological mapping, provides a database for geological hazard assessment for the study area, discussed in the next chapter.

CHAPTER 4
GEOLOGICAL HAZARD ASSESSMENT

4.1 INTRODUCTION

The following chapter is concerned with the formulation of a geological hazard zonation approach for the study area. This is based on an engineering geological approach, and utilises the information presented in earlier chapters to compile a hazard zonation map (Waikawa only) and development suitability map (whole study area). It is intended that these maps will contribute to the future safety of planned development in the study area. It is also hoped that the approach proposed in this thesis may at some time in the future be extended to cover other parts of the Marlborough Sounds.

The first sections of the following chapter background the general principles of geological hazard assessment, and examples of various approaches to hazard zonation in New Zealand and overseas are reviewed. The hazard zonation scheme and data presentation methods adopted by this study are then introduced, and are compared with existing hazard zonation systems. The chapter concludes with recommendations for extensions and additions to the proposed scheme, particularly in the field of improving the basic geotechnical and climatic databases.

The relevant legislation governing land use management in New Zealand is reviewed by Bell (1984), and is summarised in Table 4.1. At a regional level, land use planning is the function of Regional or United Councils. At a local level, the formulation and implementation of District Schemes is the responsibility of Borough and County Councils, and includes the control of land subdivision. In both cases the principal objective may be defined as:

> "the exclusion of any land unsuited ... to future urban development.
>
> (Bell, 1984)

In addition, regional catchment authorities have a statutory responsibility with regard to soil conservation and mitigation of soil erosion and flooding, and must approve any proposed engineering works likely to adversely affect any of the these factors.

Principal Act[2]	Planning Function	Comments[3]
A. *TOWN AND COUNTRY PLANNING ACT 1977*	1. *Regional Schemes*	Designed for wise use of resources and implementation of long-term "regional" planning policies; establishment of regional or united councils
	2. *District Schemes*	Detailed planning and admininstration of local "districts"; territorial authorities with responsibility for land-use and development practices
	3. *Maritime Schemes*	Preservation and conservation function in addition to establishment and administration of maritime facilities such as harbours
B. *LOCAL GOVERNMENT ACT 1974*	1. *Scheme Plans*	Local councils have responsibility for urban subdivision codes and preparation of scheme plans for residential development
	2. *By-Law Control*	Local councils also responsible for building permit approval, the adequacy of building sites, and control of earthworks or land instability
	3. *Provision of Services*	Functions of local authorities include roading, water supply, stormwater and sewerage disposal, etc
C. *SOIL CONSERVATION AND RIVERS CONTROL ACT 1941*	1. *Catchment Authorities*	Required to deal with river and erosion control, soil conservation and drainage works, including flood mitigation
	2. *Erosion Control*	Statutory powers available to control earthworks that may result in erosion or siltation
D. *WATER AND SOIL CONSERVATION ACT 1967*	1. *Regional Water Boards*	Established to control access to surface and underground water, including waste disposal and pollution
	2. *National Water and Soil Conservation Authority (NWASCO)*	Established as national coordinating authority, with research functions in areas such as erosion assessment
E. *EARTHQUAKE AND WAR DAMAGE ACT 1944*	1. *Earthquake Insurance*	Provision for compensation for earthquake shock and resultant fire damage to property
	2. *Disaster Fund*	Amendment to provide for damage due to abnormal storm, flood or volcanic eruption
	3. *Landslip Insurance*	Amendment to provide automatic cover for property damage from landslip but <u>not</u> from settlement, soil shrinkage or compaction
	4. *Geothermal Activity*	Cover available on a voluntary basis only

NOTES: 1) Table based on Sheppard (1983) and Gill (1974).

2) Various Amendments to the Principal Acts now current.

3) Only selected aspects of relevant legislation outlined.

TABLE 4.1. Land-use planning legislation in New Zealand. Diagram from Bell (1984).

4.2 PRINCIPLES OF GEOLOGICAL HAZARD ZONATION

4.2.1 Conceptual Framework

Varnes (1984), in a comprehensive international review of landslide hazard zonation techniques, identifies three basic principles as being fundamental to landslide hazard assessment. These principles are equally applicable in a broader sense to geological hazard assessment in general, and are outlined below.

(i) The past and present are the key to the future.

Known generally in the field of geology as the Principle of Uniformitarianism, this statement embodies the concept that geological, geomorphic, and hydrological conditions initiating or aggravating hazardous processes in the past will have similar consequences in the future (assuming no modification of natural conditions). Through this very general principle it is possible to estimate the nature of future problems based on the past occurrence of hazardous events.

(ii) The main conditions initiating or aggravating hazardous processes can be identified.

Leading on from above, it is possible to identify the individual factors contributing to the occurrence of a given hazardous event. In general, this information is gained through site specific engineering geological and geotechnical investigation of representative sites throughout the area in question. Use is also made of any existing data, both published and unpublished, such as geological maps, aerial photographs, historical records etc. This data may then be extrapolated with the aid of regional mapping to provide a reasonable database for the whole area.

(iii) Degrees of hazard may be estimated.

Ideally some form of probability versus magnitude relationship may be determined for each individual factor contributing to the occurrence of a hazardous event. The degree to which this is possible depends on the data and resources available to the investigator. This information is often graphically represented as individual "factor maps". Each factor may then be weighted according to its relative contribution to the occurrence of the hazardous event, and a predictive model may be developed. Such a model can then be checked and refined using data from subsequent hazardous events. Using such models the degree of hazard posed by one or more hazardous processes may be determined for a particular area, and this information presented in the form of a hazard zonation map.

This information is then passed on to land use planners and administrators, who may impose zoning restrictions to minimise the risk to urban development. Figure 4.3 outlines the conceptual approach to natural hazard assessment, based on the above principles.

4.2.2 Terminology

Some initial definition and clarification of the terms relating to hazard assessment is necessary, as different authors have tended to adopt a variety of definitions in the past.

4.2.2.1 Hazard

This study adopts the term "<u>hazardous process</u>" to refer to any natural physical process with the potential to cause damage or disruption to life, structures, services or economic activities. A <u>"hazardous event"</u> occurs when a given hazardous process actually causes damage or disruption to one or all of the above.

IPENZ (1983) defines the term "hazard" as follows:

> "A condition or situation which has the potential to create or increase harm to the people, property or the environment"

BS4778 (1979) adopts a similar definition:

> "A set of conditions in the operation of a product or system with the potential for initiating an accident sequence. Note: this term has a different meaning when used in connection with reliability."

In other words, both IPENZ (1983) and BS 4778 (1979) define the term "hazard" in the same way that this study defines "hazardous process". In contrast, Varnes (1984) defined "hazard" as:

> "The probability of occurrence within a specified period of time, and within a given area, of a potentially damaging phenomena."

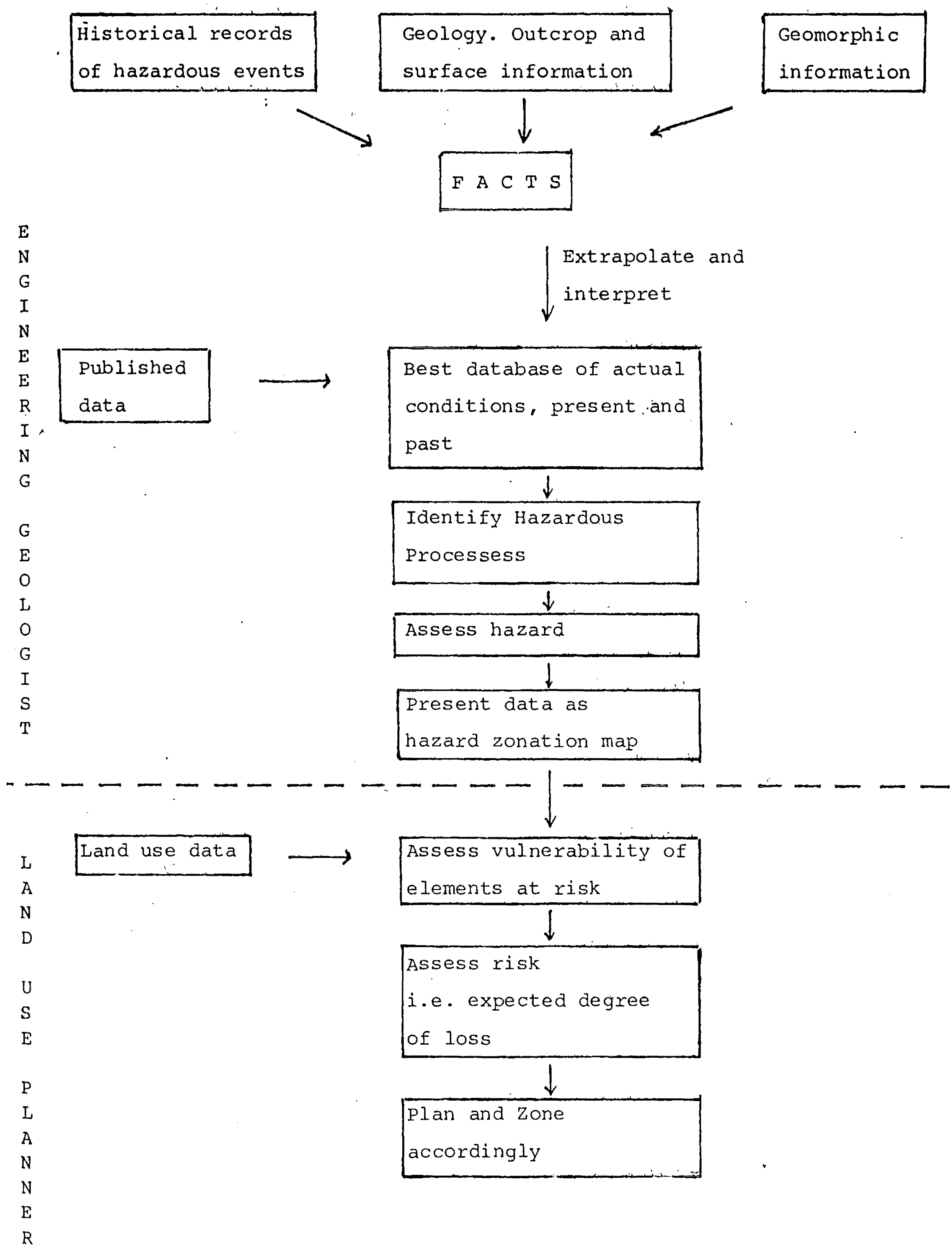


FIGURE 4.3. Flow chart outlining the idealised approach to geological hazard assessment in land use planning.

This study adopts Varnes' definition.

4.2.2.2 Risk

The is also some ambiguity associated with the term "risk" throughout the literature. Both the following definitions of "risk" embody dual meanings.

> "The combined effect of the probability of occurrence of an undesirable event, and the magnitude of the event."
>
> (BS 4778, 1979)
>
> "The probability that a potential hazard will be realised, and the probability of the harm itself."
>
> (IPENZ, 1983)

Varnes (1984) defined "risk" on the basis of the human implications of a hazardous event, rather than the probability of its occurrence, as follows.

> "The expected degree of loss due to a particular natural phenomenon"

This study adopts the above definition as it refers specifically to the consequences of a hazardous event in terms of life and property, and is thus clearly distinct from the adopted definition of <u>hazard</u> which deals with the probability of occurrence of a given magnitude hazardous event rather than human consequences.

4.2.2.3 Zonation

For the purposes of this study "zonation" is defined as the partitioning of land into areas with similar attributes for administration purposes. Thus a hazard zonation map subdivides a region into areas judged to have a similar probability of occurrence of a certain hazardous event.

4.2.2.4 Vulnerability

"Element or elements at risk" may be defined as any subset of the of the population, properties, economic activities, public services etc. at risk from a hazardous process in a given area. The term "vulnerability" refers to the expected degree of loss for a given element or group of elements at risk (expressed as 0 = no damage to 1 = total loss) (Varnes, 1984).

A simple example may be used to illustrate the usage of the terms "hazard" and "risk " as adopted by this study. An avalanche in an unpopulated alpine area would be expected to have a high degree of "hazard" (i.e. high probability of occurrence), but a low "risk" (i.e. damage to life and property would be negligible). On the contrary, the occurrence of a volcanic eruption in an urban area would have a low degree of "hazard", but a very high "risk".

Thus a hazard zonation map is based solely on a consideration of the hazardous processes affecting a given area, while a risk zonation map extends this to consider the nature of the elements at risk, and assess their vulnerability

4.2.3 The Role of Engineering Geology

This study adopts the "engineering geological approach" to natural hazard assessment and subdivision planning outlined by Bell and Pettinga (1984). Table 4.2 outlines the types of engineering geological data input required for urban planning at a variety of scales. The maps produced as a result of this thesis are presented at scales of 1:5000-1:10000, and therefore fall into the "District Scheme" planning stage.

Engineering geology may be defined as both the evaluation of active processes potentially affecting a given site, and the systematic recording of foundation conditions (Bell, 1979). With these objectives in mind, geological and geotechnical information is collected through simple and relatively cheap site investigation methods (such as those described in chapter 3). A "site" model is then developed to integrate this information, allowing (i) the determination of areas requiring further detailed geotechnical investigation, and (ii) the delineation of areas unsuitable for development due to geological or geotechnical constraints (Bell and Pettinga, 1984).

This study follows such an approach to develop a hazard zonation scheme for the Waikawa area. Site models have been developed for various hazardous processes identified at specific localities in the Waikawa Bay area, and this information is then extrapolated to model similar

Planning Stage[1]	Engineering Geology[2] Investigation Objectives	Typical Map Scales	Geotechnical Data[3]
A. REGIONAL SCHEME	1. Identification of "regional" hazards such as floodplains and "active" fault traces 2. Mapping of bedrock and surficial geology	1:100,000 ↓ 1:25,000	Characterisation of lithologies and identification of "problem" soil types; assessment of resources (e.g. aggregate availability and long-term requirements)
B. DISTRICT SCHEME	1. Engineering geological and/or pedological mapping, with limited excavation logging 2. Identification and investigation of "local" hazards (e.g. landslides)	1:10,000 ↓ 1:5,000	Geotechnical characterisation of mapping units as required for land-use zoning decisions; specific evaluation of tectonic and hydrologic hazards
C. SUBDIVISION CONCEPT PLAN	1. Engineering geological site mapping and subsurface investigations 2. Interpretative risk assessment and/or planning guidelines	1:2,000 ↓ 1:1,000	Limited testing (e.g. plasticity/grainsize) to indicate general characteristics of site materials; hazard avoidance or mitigation measures
D. SUBDIVISION SCHEME PLANS	1. Detailed site investigation of specific areas identified at Concept Plan stage 2. Engineering geological mapping and logging to meet any "local" authority requirements	1:1,000 ↓ 1:500	Additional geotechnical testing to verify design and/or construction feasibility as required; investigation of specific features to facilitate stage E
E. SUBDIVISION DESIGN AND CONSTRUCTION	1. Confirmation of mapped geology 2. Additional investigation as required	1:500 ↓ 1:50	Detailed investigations for design of cut and fill batters if required; control of earthworks
F. SECTION DEVELOPMENT AND HOUSE CONSTRUCTION	Engineering geological investigations only if required (A → E should prevent site "problems")	1:200 ↓ 1:50	Site specific testing for foundations if required; control of earthworks, drainage, etc

NOTES: 1) Planning stages follow from existing legislative framework (Table 3).

2) Engineering geology investigation methods include air-photo interpretation and relevant mapping and logging techniques.

3) Geotechnical design investigation requirements may vary considerably within individual urban areas.

TABLE 4.2 Engineering geological input for urban planning in New Zealand. Diagram from Bell (1984).

processes active or potentially active throughout the area. In this way areas at risk from hazardous processes may be identified (hazard zonation map, Figure 4.1) and recommendations made as to those areas which are most suitable for future development (development suitability map, Figure 4.2)

4.3 REVIEW OF HAZARD ZONATION SCHEMES CURRENTLY IN USE.

4.3.1 Introduction

The following section reviews a number of hazard zonation schemes presently in use both in New Zealand and overseas. Rather than attempting an exhaustive review of the large amount of information published in recent literature, several examples are discussed to illustrate the range of methods currently being employed in the context of both regional and local planning. Extensive general literature reviews on this topic include Varnes (1984), and Brabb (1984), while Bell (1987) reviews current New Zealand practices. Comparisons between the approach proposed in this study and existing systems of hazard zonation are given in section 4.5.6.

4.3.2 Geotechnical Area Studies Programme (G.A.S.P.), Hong Kong

The Geotechnical Control Office in Hong Kong has developed a system of terrain evaluation to cope with the problems of high density urban development in steep landslide-prone terrain. Terrain evaluation or analysis may be defined as the technique of classifying areas of land on the basis of similar physical attributes. The results of geotechnical investigations undertaken at a particular locality may then be considered representative of a particular class of terrain. This information may be presented in map form, and a series of further maps may subsequently be derived from this basic information for various applications in the fields of both engineering and planning.

Terrain classification in Hong Kong is undertaken at a regional scale (1:20000) on the basis of slope gradient, terrain component and the nature of erosion and instability problems. At the "district" scale (1:2500), terrain classification is based on slope gradient, terrain component, terrain morphology, the nature of erosion and instability, hydrology, vegetation and slope condition (i.e. degree of cutting and filling). Tables 4.3 and 4.4 outline the standardised classification schedules used at both scales. This information is presented as terrain classification maps, which form a database for a series of planning and individual factor maps. Maps showing landform type, vegetation, erosion, surface hydrology and engineering geology are prepared from the terrain classification map, augmented by air photograph interpretation and existing information where appropriate.

A Geotechnical Land Use Map (GLUM) divides the terrain into 4 classes on the basis of an assessment of the overall geotechnical limitations to urban development. The definition of these classes is outlined in Table 4.5. GLUM class I areas are characterised by a low level of geotechnical limitations to development, and therefore the highest suitability for development. GLUM class II and III areas are characterised by moderate and high geotechnical limitations respectively, and GLUM class IV areas are defined as areas with extreme geotechnical limitations on which development should be avoided if possible.

A "physical constraints map" is also prepared from the terrain classification map, indicating the types of constraints on urban development in a particular area. Such constraints include the presence of colluvium, zones of instability, slopes exceeding 30°, disturbed terrain (i.e. areas of cutting and filling), zones of gully erosion and floodplains. The physical constraints map is therefore designed as a supplement to the GLUM. The derivation and inter-relationships of these maps is presented diagrammatically in Figure 4.4.

In addition to the above maps, a General Limitations and Engineering Appraisal Map (GLEAM) is prepared at the 1:20000 scale only. This map is designed specifically as an aid to land use planning, and identifies land suitable for future development. It represents a generalisation and synthesis of both the G.L.U.M. and physical constraints map. The principle applications of the various maps described above are outlined in Table 4.6.

Intensive geotechnical investigations in some areas of Hong Kong have allowed a critical evaluation of this terrain classification and

(a) Slope Gradient	Code
0 - 5°	1
5 - 15°	2
15 - 30°	3
30 - 40°	4
40 - 60°	5
>60°	6

(b) Terrain Component	Code
Hillcrest or ridge	A
Sideslope - straight	B
- concave	C
- convex	D
Footslope (colluvium) - straight	E
- concave	F
- convex	G
Drainage plain (colluvium)	H
Floodplain	I
Coastal plain	K
Litoral zone	L
Rock outcrop	M
Cut - straight	N
- concave	O
- convex	P
Fill - straight	R
- concave	S
- convex	T
General disturbed terrain	V
Alluvial plain	X
Reclamation	Z
Waterbodies :	
Natural stream	1
Man-made channel	2
Water storage	3
Fish pond	4

(c) Erosion and Instability	Code
No appreciable erosion	
Sheet erosion - minor	1
- moderate	2
- severe	3
Rill erosion - minor	4
- moderate	5
- severe	6
Gully erosion - minor	7
- moderate	8
- severe	9
Well-defined recent landslip, >1 ha in size	a
General instability - relict	n
- recent	r
Coastal instability	w

TABLE 4.3. Standardised terrain classification schedule used for 1:20000 mapping under the GASP programme. Diagram from Brand (1988).

(a) Slope Gradient	Code
0 - 5°	A
5 - 15°	B
15 - 30°	C
30 - 40°	D
40 - 60°	E
>60°	F

(b) Terrain Component	Code
Hillcrest	1
Ridge	2
Sideslope	3
Footslope	4
Drainage plain	5
Incised drainage channel	6
Disturbed terrain	7
Disturbed terrain/drainage	8
Rock exposure	9
Alluvial plain	10
Floodplain	11
Coastal plain	12
Stream course (perennial)	13
Stream course with rock exposure in bed (perennial)	14
Stream course with rock exposure in bed (ephemeral)	15
Man-made channel (including catchwaters)	16
Water storage	17
Swamp/marsh	18
Reclamation	19
Beach	20
Dune	21

(c) Terrain Morphology	Code
Straight - insitu terrain	a
Concave - insitu terrain	b
Convex - insitu terrain	c
Straight - colluvium	d
Concave - colluvium	e
Convex - colluvium	f
Straight - < 2m thick colluvium	g
Concave - < 2m thick colluvium	h
Convex - < 2m thick colluvium	i
Straight - corestones on insitu	j
Concave - corestones on insitu	k
Convex - corestones on insitu	l
Straight - alluvium	m
Concave - alluvium	n
Convex - alluvium	o

(d) Erosion & Instability	Code
No appreciable erosion	1
Well-defined landslip - integral	2a
- scar	2b
- debris	2c
General instability - colluvium	2d
- insitu	2e
Sheet erosion - minor (1-10% bare)	3a
- moderate (10-40%)	3b
- severe (>40%)	3c
Rill erosion - minor	4a
- moderate	4b
- severe	4c
Gully erosion - minor	5a
- moderate	5b
- severe	5c
Highly jointed rock exposure, or boulders	6

(e) Slope Condition	Code
Cut, 0 - 5 m	1
5 - 10 m	3
10 - 20 m	5
20 - 30 m	7
>30 m	9
Fill, 0 - 5 m	2
5 - 15 m	4
15 - 30 m	6

(f) Hydrology	Code
Inlet zone	a
Outlet zone	b
Water ponding area	c
Subsurface flow	d

(g) Vegetation	Code
Grassland	1
Shrubland	2
Mixed broadleaf woodland	3
Cultivated land	4
Non-vegetated - soil	5
- rock	6
- built upon	7
Reafforestation	8

TABLE 4.4. Terrain classification schedule for 1:2500 mapping under the GASP programme. Diagram from Brand (1988).

GLUM Class Characteristics	Class I	Class II	Class III	Class IV
Geotechnical Limitations	Low	Moderate	High	Extreme
Suitability for Development	High	Moderate	Low	Probably unsuitable
Engineering Costs for Development	Low	Normal	High	Very high
Intensity of Site Investigation Required	Normal	Normal	Intensive	Very intensive
Examples of Terrain in GLUM Class	1. Insitu terrain <15°, minor erosion. 2. Cut platforms in insitu terrain. 3. Cut slope <15°, <30m high in insitu terrain.	1. Insitu terrain 15-30°, no instability or severe erosion. 2. Insitu terrain <15°, severe erosion. 3. Colluvium <15°, no instability or severe erosion.	1. Insitu terrain 30-60°, no instability or severe erosion. 2. Insitu terrain <15°, history of landslips. 3. Colluvium <15°, general instability.	1. Insitu terrain >60°. 2. Insitu terrain 30-60°, instability or severe erosion. 3. Colluvium 30-60°, moderate erosion.

TABLE 4.5. Definition of the "GLUM" classes used by the GASP programme. Diagram from Brand (1988).

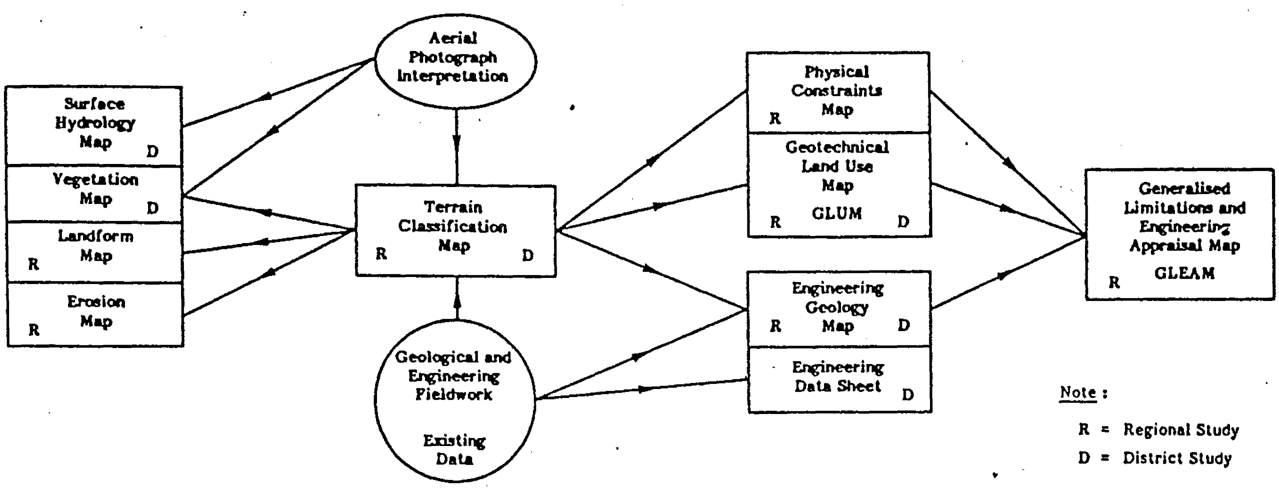


FIGURE 4.4. The derivation and inter-relationships of the various maps prepared during GASP studies. Diagram from Brand (1988).

Name of Map	Type of Map	GASP Scale		Value of Map to Users (maximum = •••)				
		Regional 1:20 000	District 1:2 500	Planner	Landscape Architect	Estate Surveyor	Civil Engineer	Geotechnical Engineer
Terrain Classification	Basic data	✓	✓	•	•	•	•	•
Landform	Derivative	✓		••	••	•	•	•
Erosion	Derivative	✓		••	••	•	••	••
Surface Hydrology	Derivative		✓	•	••	•	•••	•••
Vegetation	Basic data		✓	••	•••	•	•	•
Engineering Geology	Basic data/ Interpretative	✓	✓	•	•	•	••	•••
Engineering Data Sheet	Basic data		✓	•	•	•	••	•••
Physical Constraints	Interpretative	✓		•••	••	•	•••	•••
GLUM	Interpretative	✓	✓	•••	••	•••	•••	••
GLEAM	Interpretative	✓		•••	••	••	•••	•••

TABLE 4.6. The applications of the various maps produced by GASP studies. Diagram from Brand (1988).

	Slope		
	<5%	5–15%	>15%
No landslide deposits	1 Stable	2 Generally stable	3 Moderately stable
Susceptible bedrock			4 moderately unstable
Susceptible surficial deposits	1A Subject to liquefaction	None	
Landslide deposits		5 Unstable	

TABLE 4.7. Slope stability classification system used by Nilsen at al (1978) for regional landslide hazard mapping in the San Fransisco Bay area.

associated mapping approach, and the results have proved highly satisfactory (Brand, 1988).

4.3.3 The PUCE System of Terrain Classification, Australia

The Australian PUCE system is essentially a technique whereby terrain is classified in terms of the nature of underlying bedrock, surface morphology, land use and vegetation cover. This system aims to provide a rationalised method of geotechnical resource capability assessment on a national basis (Grant and Finlayson, 1978). Maps displaying this information may subsequently be used in a wide range of applications, including geological hazard assessment, and land use planning.

The PUCE system classifies terrain into areas of similar physical features and properties. This system subdivides a study region into individual "provinces", "terrain patterns", "terrain units" and "terrain components", each being a further subclassification of the last. Individual "provinces" are defined on the basis of bedrock lithology and age; "terrain patterns" are defined on the basis of relief amplitude and stream density; "terrain units" are classified according to landforms, soil profiles and vegetation, and "terrain components" are classified on the basis of slope angle, slope form, soil horizons, land use/land cover, and vegetation (Finlayson, 1984). A set of numerically coded standardised alternatives have been defined for each of the physical parameters (described above).

Given such a database it is then possible to identify those areas whose physical attributes dispose them to one or more hazardous processes, and to compile hazard maps accordingly. Terrain evaluation information following the PUCE system is available for large areas of eastern Australia, and has been applied to engineering geological and land use capability assessments in the Sydney and Moreton Bay areas (Finlayson, 1984). The system has, however, become rather complex as it has developed, and is most suited to computer processing using digitised information (Brand, 1988).

4.3.4 The ZERMOS Programme, France

The French ZERMOS (Zones Exposed to Risk of Soil Movement) system represents another effort to derive a nationally consistent approach to landslide hazard mapping. While the methodology is still being developed, Varnes (1984) presents several examples of studies completed under the ZERMOS programme. The following discussion is based on an example of the application of the ZERMOS system to slope instability hazard assessment in the Moyenne-Vesubie area of France (Meneroud and Calvino, 1979).

Landslide hazard mapping is based on the presence or absence of a number of "determining factors". These are physical factors which influence the occurrence and magnitude of landslide events, and include lithology, slope, morphology, hydrology, structure, and kinematics (i.e. the rate of landslide movement). These factors are assessed for all types of slope instability active in the mapping area. Those areas where all determining factors are present are assigned the highest hazard level, while those areas free of all determining factors are assigned the lowest hazard level. Two intermediate hazard levels are also defined on the basis of the number of determining factors present. The ZERMOS system permits the use of up to 7 hazard levels, and this data is presented in the form of 1:25000 hazard maps, with accompanying text.

This approach relies heavily on the identification and consideration of the geomorphic processes affecting the mapping area, and the resultant influence on slope stability. As such the hazard map produced also contains a large amount of geomorphic information.

4.3.5 Relative Slope Stability Mapping, San Franscisco Bay, U.S.A.

A system of landslide susceptibility mapping based on evaluation of the susceptibility of each individual geological unit to landsliding was developed by Brabb et al (1972) for San Mateo County, California. This was accomplished by superimposing landslide inventory maps over bedrock outcrop maps, and determining the quantitative relationship between outcrop area and the number of landslides occurring within each unit (i.e. determining the percentage area of each geological unit affected by landslides). On the basis of this information each geological unit was then assigned a landslide susceptibility class.

Slope maps were then superimposed on to this data, and the maximum frequency of landslide occurrence for each slope interval was determined for each bedrock unit. Areas within the slope interval having the maximum occurrence of landslides were assigned the same susceptibility rating as the underlying bedrock unit, while the susceptibility rating was progressively decreased for areas falling within slope intervals showing fewer landslides. This approach is considered by Varnes (1984) to be one of the most widely used in the United States at that time.

A similar approach was adopted by Nilsen et al (1978), who prepared relative slope stability maps for the San Franscisco Bay area at a scale of 1:125000. Existing geological and slope angle maps were used, and landslides were mapped from aerial photographs. The six slope stability categories employed are simpler than the system used by Brabb et al (1972), and are defined in Table 4.7.

Both of the above systems are examples of regional approaches to hazard assessment, and are intended to indicate both the degree and distribution of a single hazardous process (landsliding) for very large areas. As such, the maps produced are intended as guides to regional planning as opposed to providing site specific information.

4.3.6 Urban Land Use Capability Surveys, New Zealand.

Urban Land Use Capability Surveys have been developed by the National Water and Soil Conservation Organisation to assist local authorities with their statutory planning responsibilities in urban fringe areas (Jessen, 1987). The surveys utilises a system of terrain classification based on an inventory of physical features including rock type, soil type, landform, degree of erosion, drainage, land cover and land use. Figure 4.5 also outlines the full ULUC survey system. The area in question is subdivided into a series of inventory map units, which are defined as areas in which all the physical factors listed above are constant. Each such unit is identified with a complex code describing the nature of each of these factors.

From this information, the relevant physical constraints to urban developed are assessed for each inventory map unit described above, and presented on "constraint" maps. Typical constraints on urban development include coastal erosion, debris deposition, flooding, foundation inadequacy, mass movement, poor drainage, and steep topography. Each

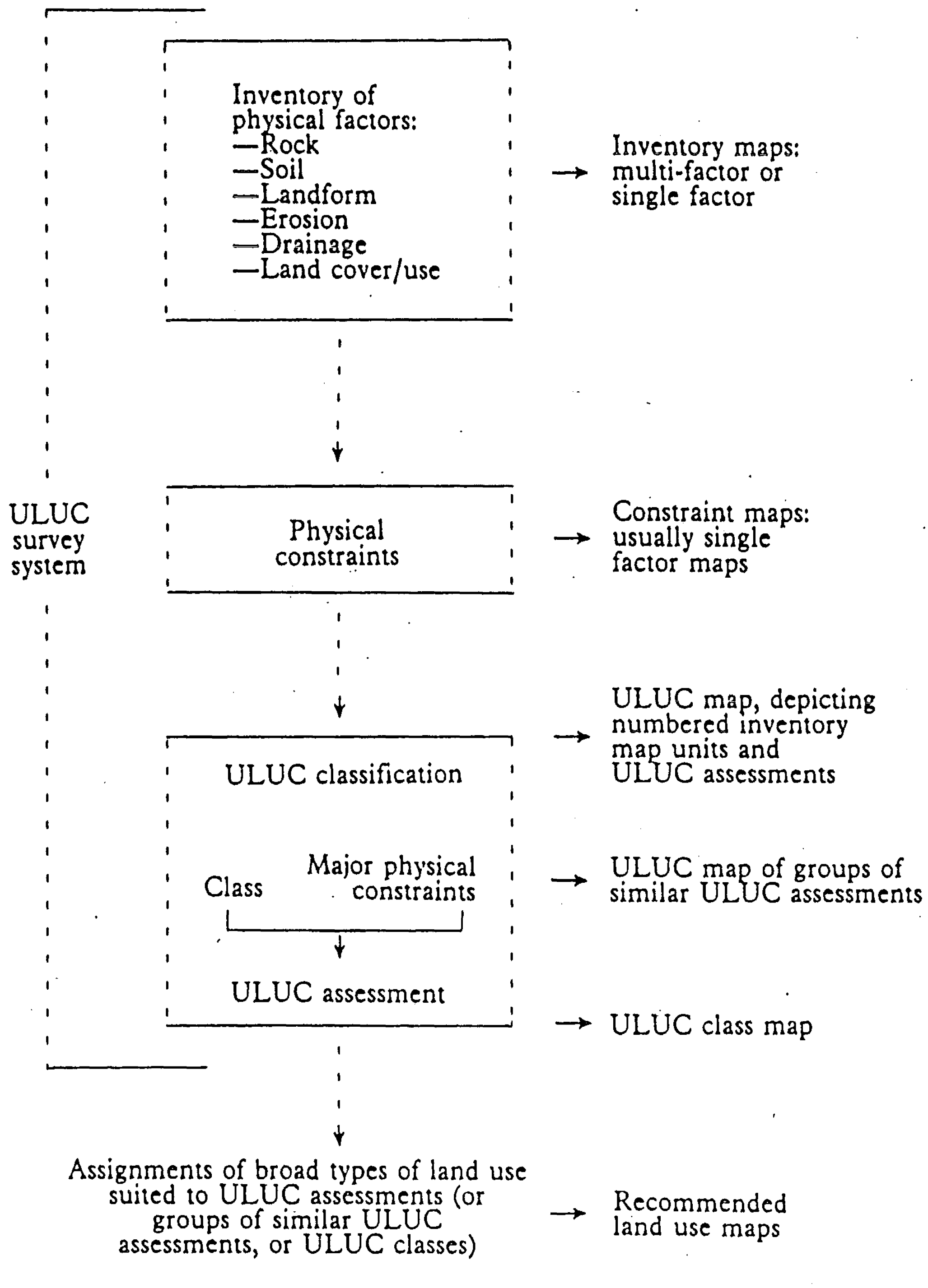


FIGURE 4.5. Flow chart outlining the ULUC survey system. Daigram from Jessen (1987).

ULUC class A—Land with negligible, or no, physical constraints to urban development and use.
ULUC class B—Land with slight physical constraints to urban development and use.
ULUC class C—Land with moderate physical constraints to urban development and use.
ULUC class D—Land with severe physical constraints to urban development and use.
ULUC class E—Land with physical constraints so severe that they essentially preclude any kind of urban land development.

FIGURE 4.6. Definition of ULUC classes. Diagram from Jessen (1987).

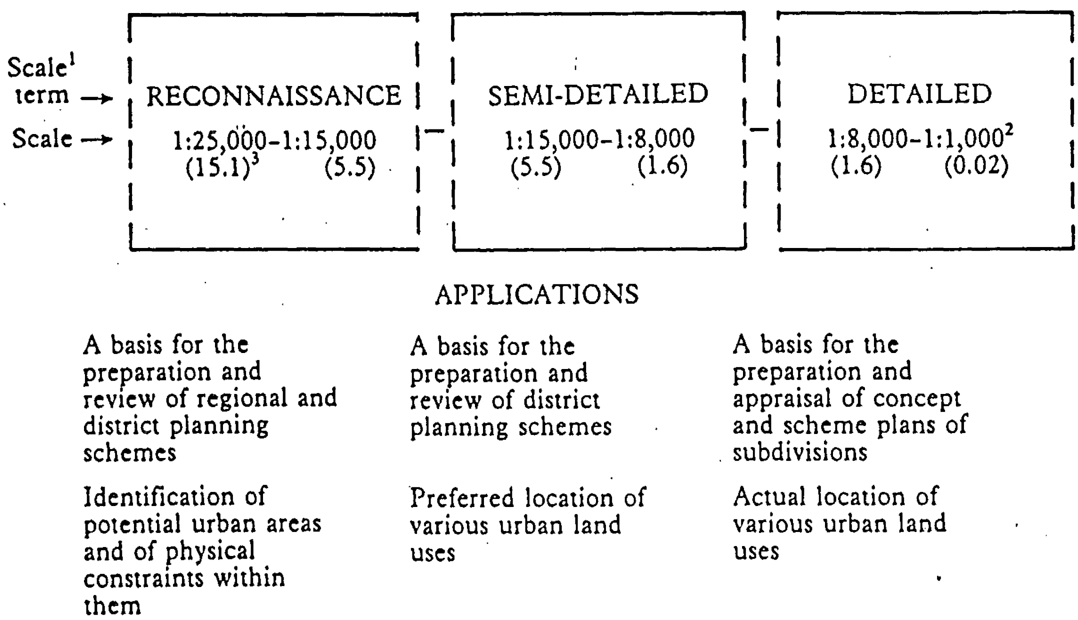


FIGURE 4.7. The application of ULUC surveys at various scales. Diagram from Jessen (1987).

individual constraint is assigned a severity rating (ranging from 0 = negligible to 3 = severe) on the basis of a subjective assessment, augmented by any available data on event periodicity.

Following consideration of all the above data the area is then zoned into 4 or 5 urban land use capability classes (see Figure 4.6) ranging from class A (most suitable for development) to class E (least suitable for development). The assignment of ULUC classes is primarily based on a subjective consideration of the nature and severity of the various constraints discussed above.

These surveys may be undertaken at a variety of scales, ranging from reconnaissance (1:25000-1:15000), to semi-detailed (1:15000-1:8000), to detailed (1:8000-1:1000). The applications of U.L.U.C. surveys at these various scales are outlined in Figure 4.7. This approach has been applied in a number of areas throughout New Zealand to date, including the Otago Peninsula (Robins, 1983) and the Eastbourne Borough (Lawrence et al, 1982). Lawrence, (1981) further discusses the use of ULUC surveys in other areas of New Zealand in recent years.

4.3.7 Discussion.

Many of the fundamental differences between the various approaches outlined above arise as a result of the varying scales of investigation. The slope stability mapping efforts of Brabb et al (1972) and Nilsen (1978) cover large areas at scales of 1:60000 to 1:125000, and adopt very generalised systems of mapping units. In contrast, the 1:2500 district scale terrain classification undertaken by the Geotechnical Control Office in Hong Kong ultilises a far more detailed schedule of terrain classification. Clearly increased detail is required as the scale of investigation decreases. The use of the same schedule of terrain classification by the ULUC survey system at all scales between 1:25000 and 1:1000 is considered to be a weakness as it does not reflect the need for increased detail at smaller scales.

The degree of detail and accuracy of a particular system of hazard assessment and land use management depends to a large extent on (i) the financial resources of the study, and (ii) the quality of any existing geotechnical information. While the methodology employed by the GASP programme is felt to give very detailed and accurate results, the major economic implications of land use planning decisions in the Hong Kong metropolitan area obviously warrant a far greater financial investment per unit area than larger scale reconnaissance techniques such as PUCE and ZERMOS. Similarly a considerable amount of geotechnical information in the form of site specific investigation results and construction records is available in an area like Hong Kong, while such information may be severely limited in rural or poorly developed areas (much of the Waikawa residential area, for example).

Published information in the form of geological and pedological maps in New Zealand is restricted in detail, and includes limited data on surficial geology (Hancox, 1981). The overseas systems described above generally require a high standard of basic engineering geological information. Clearly such systems would not be applicable where detailed medium to small scale (1:50000 or less) geological maps are not available.

It is also felt that systems of terrain classification based primarily on land surface features, such as the ULUC system and the PUCE system, do not give sufficient attention to the engineering properties of the subsurface geology. Similarly, neither of these systems emphasise the identification of active or potentially active geological processes as such. In contrast, hazard evaluation in Hong Kong (the GASP programme) includes the production of a specific engineering geological map as a contribution to the final GLUM maps.

While terrain evaluation based on a standarised series of physical attributes is a convenient method of data acquisition, some understanding and consideration of active geological and geomorphic processes is also important. It is felt that a combination of terrain evaluation and engineering geological input is necessary in any assessment of geological hazards. The hazard assessment approach proposed by this study for the Waikawa residential area is based primarily on an engineering geological assessment of both geological materials and active geological processes.

4.4 HAZARDOUS PROCESSES IN THE PICTON REGION

4.4.1 Slope Movements.

Slope movements in the form of debris slide-flows in colluvium are relatively common in the upper catchments of the study area (see Figure 4.8), although in the past these have generally occurred well away from residential development. As development is now beginning to encroach on to these steeper slopes, greater consideration of the potential landslide hazard is necessary.

Landsliding in colluvium is directly related to prolonged or intense rainfall episodes. It follows that any attempt to quantify landslide hazard requires detailed information on the frequency and magnitude of these rainfall episodes. It appears that a threshold value of soil water content exists, above which landsliding may be expected. Crozier and Eyles (1980) investigated threshold soil water conditions for the onset of landsliding in the Otago Peninsula and Wellington areas. This approach takes into account both rainfall on the day in question, and the effects of antecedent precipitation. Clearly such an approach requires both detailed information on rainfall duration and intensity, and accurate records of the occurrence of landslide events, neither of which are readily available for the Picton area. Neither does this technique allow for the effect of man made disturbance to the natural landscape, which may adversely effect slope stability. A large number of landslides have occurred in the Picton area as a result of the disturbance of natural drainage by excavations (chiefly roading).

Similarly, a lack of detailed geotechnical information, coupled with the geological variability of the area (particularly subsurface hydrological conditions) invalidates the use of numerical methods of slope stability analysis. Landslide hazard assessment for this study is instead based on the identification of areas of past slope instability, and associated estimates of the age of the most recent activity. From air photograph interpretation and field mapping it is clear that the majority of recent landslide events are the result of partial re-activation of older slope failures.

FIGURE 4.8. Landslides in natural ground (arrowed) behind the Waikawa Marina.

FIGURE 4.9. Coastal erosion, eastern Waikawa Bay.

4.4.2 Inundation by flooding

The Waikawa Stream has a history of flooding, although quantitative records are limited. On July 24, 1987 140 mm of rain was recorded over 12 hours in the lower catchment (and was probably higher in the upper catchment), which resulted in what has been tentatively assigned as a 50 year flood (Marlborough Catchment Board, pers. comm., 1988). A peak flow of up to 30 cumecs was estimated for the Waikawa Stream, and this flood caused significant damage to the recently placed stream bank armouring below the Waikawa Road bridge. Following this event, protection works (armouring, stop bank construction and channel straightening) below the bridge were improved and are now thought adequate to cope with a 50 year event. Significant areas of the Waikawa Stream floodplain above the bridge were also inundated (much of the W_5 surface, Figure 3.2) although no residential dwellings were affected.

Until recently no development was permitted below the bridge within a "flood hazard zone", which was shown extending approximately 3 to 5 metres either side of the active channel on the Marlborough County Councils planning map No. 47a. This restriction has since been removed, and the Picton Borough Council has adopted a system whereby any building adjacent to the stream must conform to a series of minimum floor heights as defined by the Council. This does afford some protection against inundation of the buildings themselves, but the associated hazards of debris deposition and siltation still have the potential to cause considerable damage to property in an extreme rainfall event.

A number of high intensity rainfall events have occurred in the Wellington and Marlborough areas in recent years. Bell (1976) discussed the extensive flood and mass movement damage that occurred on the Kaikoura coast during Cyclone Alison, on the 11-12th of March, 1975. Rainfall figures in excess of 500 mm over a 48 hour period were recorded just north of Kaikoura. Widespread flooding and slope instability was recorded in the southern Wellington region following 200-300 mm of rainfall in a 12 hour period on the 20th of December, 1976 (Riddolls, 1977 and Eyles et al, 1978). More recently, debris movement and landslides caused considerable damage on D'Urville Island in the outer Marlborough Sounds earlier this year (1989). During this storm rainfalls of 475 mm (Catherine Cove) and 558 mm (Port Ligar) were recorded over a

48 hour period (Mr. R. Sutherland, Marlborough Catchment Board pers. comms., 1/6/1989).

Should an event such as those described above occur in the upper Waikawa Stream catchment, a wide range of problems could be expected, including landsliding on steeper slopes, and debris deposition and flooding in the lower catchment areas. As there has been no significant development to date of the low-lying areas of the floodplain above the bridge, no flood protection works have yet been constructed. As this land is presently zoned Residential "A" (i.e. suitable for high density residential development), it is clear that extensive channel confinement and flood control measures will be required before development proceeds.

4.4.3 Debris Deposition

Rapid channel aggradation resulting from deposition of alluvial debris during high intensity rainfall events is identified as a posing a hazard to urban development in the Waikawa region. Should rainfall be sufficient to initiate widespread landsliding in the upper catchment areas, a considerable volume of saturated greywacke colluvium could find its way into already swollen streams. The resulting debris slurry would flow rapidly downstream due to initially high channel gradients. Any sudden decrease in gradient, such as exists at the boundary between steep bedrock slopes and alluvial flats, is likely to result in overflow, with subsequent rapid channel migration and debris deposition. The extensive east Waikawa alluvial fan surfaces are highlighted as being most at risk during such an event, as they represent sites of considerable alluvial aggradation from similar events in the past. The lower lying areas of the Waikawa Stream floodplain would also be at risk should the stream change course, or existing flood protection works fail. It should be noted that although large areas of the Waikawa residential area are shown on Figure 3.2 to be at risk from this process, it is highly unlikely that the whole area would be affected by a single event.

Mitigation of the risk to development by debris deposition and movement consists of ensuring that culverts and watercourses have sufficient capacity to cope with rock and soil debris as well as large volumes of water. Special design of culvert intakes and outfalls is necessary to prevent intake blockage by debris and scouring in the region of the outfall.

Efficient long term maintenance and periodic clearing is also important. Obviously it is not possible to make allowances for the maximum conceivable event, but it is felt that many the present culverts and watercourses in the east Waikawa area are inadequate to cope with any significant debris movement.

4.4.4 Stream Bank Erosion

Progressive removal of material at the stream bank is occurring along several stretches of the Waikawa stream (see Figure 4.10), in places in the order of 1-2 metres annually. This is a result of the natural process of active channel migration across the recent floodplain surface. The land surface area directly affected by this process is minimal, although remedial measures would definitely be required prior to any residential development on site with stream frontage. In most cases the majority of damage occurs in flood events, and any preventative works should be designed with this in mind. The Marlborough County Council prohibits building within 8 metres of any watercourse without special dispensation, and this restriction would seem to be appropriate for the Waikawa region also. Those sections of the Waikawa Stream highlighted in Figure 4.1 as being especially prone to stream bank erosion may, however, require further investigation before building is permitted on sites bounded by the Stream.

Channel erosion and scouring also occurs on steeper slopes where streams are generally deeply incised, and have relatively high channel gradients (see Figure 4.11). The movement of large amounts of debris and water down streams which normally support only minimal flow may cause significant scouring and erosion, as occurred at Wharatekura Bay (Mr. Campbell-Board's property) during the storm of 26 July, 1985. Areas affected by this process are not shown on the hazard map (Figure 4.1, map pocket) as problems are generally confined to the stream channel. The potential for lateral erosion in these situations is minimal provided there is no significant modification of the channel itself, and that culverts are of sufficient size to cope with both debris and water.

FIGURE 4.10. Stream bank erosion, Waikawa Stream.

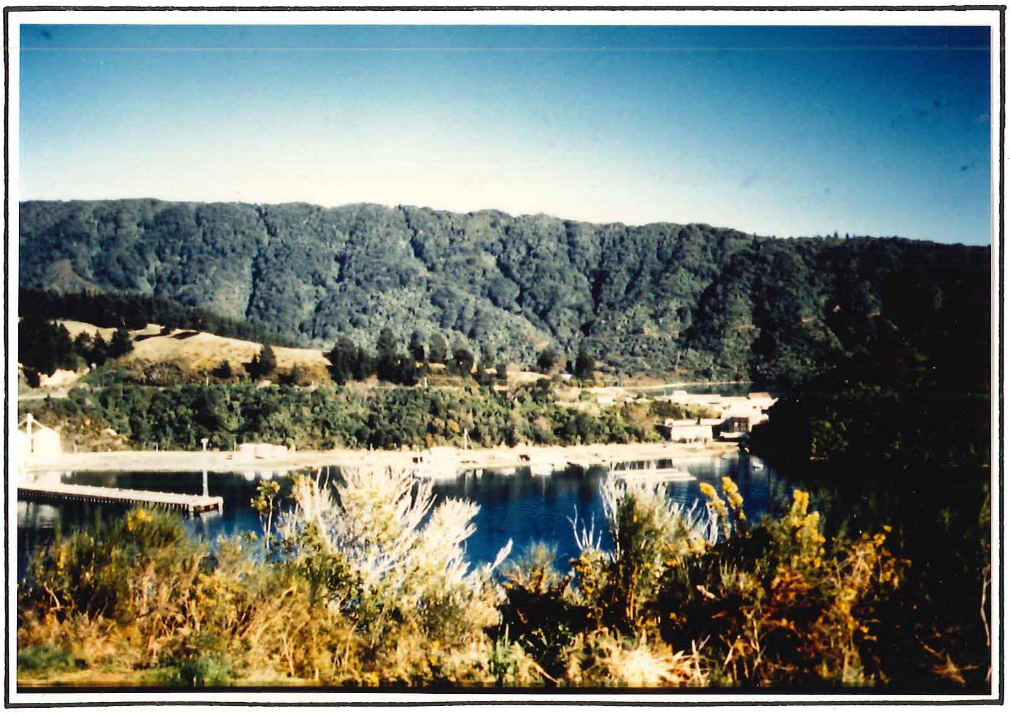


FIGURE 4.11. Changes in vegetation patterns suggest periodic gully scouring has occurred on the steep slopes on the western side of Shakespeare Bay (background).

4.4.5 Coastal Erosion

Coastal erosion is affecting some stretches of coastline in the Waikawa Bay area (see Figure 4.9). While some erosion and oversteepening at the shoreline is attributed to natural wave action, particularly on the more exposed north-west facing sections, much of the damage is the result of waves generated by the passage of the Cook Strait Rail Ferries, and an increasing number of smaller pleasure craft.

The steep nature of the terrain adjacent to the shoreline makes the construction of retaining walls economically dubious in many cases. The construction of groynes to trap sediments and form a "buffer" between the waves and the easily eroded weathered bedrock has proved effective in some cases, with the added advantage of "creating" a beach (Mr. K. Campbell-Board, pers. comms., 1989). With a likely continued increase in marine traffic, current sites of coastal erosion are best avoided for residential development.

4.4.6 High Water Table

Areas of high water table (i.e. permanently ponded drainage) are identified on the hazard map as they represent both areas permanent inundation, and areas of potential ground subsidence. The former obviously prohibits further development without site de-watering and filling. Highly organic sediments associated with swampy ground are prone to subside due to decomposition of their organic components, particularly under the weight of land fill. Investigation of the nature and depth of swamp sediments (by hand auguring, drilling, or trenching) would be required prior to filling. Removal of organic sediments may be necessary before development proceeds.

4.4.7 Seismicity

The Picton area is situated in one of the most seismically active regions in New Zealand (Smith and Berryman, 1983). The associated hazards of ground rupture, ground shaking and earth deformation warrant consideration from an urban planning point of view. The presence of a discernible trace of the Waikawa Fault, together with associated seismic deformation in Holocene aged alluvial gravels, is evidence that seismic activity centred within the study area has occurred in Late Quaternary times, and almost certainly within the last 5000 years (see section 3.6). Given the poor definition of the fault trace, and the lack of information on fault activity it is not felt appropriate to recommend any restriction on residential development adjacent to the fault. Further investigations of the risks of ground rupture are warranted, and should preferably be undertaken prior to the further development of properties straddling the fault trace.

The risk to residential development through ground shaking is far more likely to originate from earthquakes centred outside the study area. Analysis of earthquake felt intensity records for the Picton reporting area since 1822 (records provided by Mr. M. Lowry, DSIR Geophysics Division, pers. comms., 4/10/1988, and Mr. W. D. Smith, NZ Seimological Observatory, pers. comms., 6/10/1989) yields the frequency of occurrence of various intensity events within this period (Table 4.8). Intensity figures are expressed in terms of the Modified Mercalli scale (see Table 4.9) which categorises earthquakes on the basis of qualitative damage estimates furnished by local observers. Intensity figures are therefore local parameters, and may not be directly proportional to the magnitude of the earthquake, which is a measure of the total energy released, and is constant for a given event.

These figures are in reasonable agreement with those calculated for Blenheim by Smith and Berryman (1983), in a quantitative assessment of earthquake hazard in New Zealand. While site specific assessment of earthquake hazard requires consideration of many other related factors, these figures do show that earthquakes capable of causing significant damage to residential structures and services have been felt in the Picton region in since 1822, and may be expected to recur within a similar time frame. Seismic hazard zonation is not included in the hazard map produced for the Waikawa area as this highly specialised technique is beyond the scope and resources of this project.

In general, lower catchment areas underlain by poorly consolidated alluvial gravels may be expected to experience greater ground shaking than areas underlain by in-situ bedrock. As the steeper slopes of the study area are prone to mass movements, the possibility of earthquake initiated landsliding also exists, particularly in wet weather. It is

MAGNITUDE*	NO.OF EVENTS	RETURN PERIOD (years) Picton (this study)	Blenheim (Smith and Berryma 1983)
MM IX	1	167+	210
MM VIII	2	81	58
MM VII	11	14.7	17
MM VI	24	6.75	5
MM V	67	0.41	-

TABLE 4.8. Computed return periods for various magnitude earthquakes in Picton and Blenheim.

Intensity	*Description of characteristic effects*	*Maximum acceleration of the ground*	*Magnitude corresponding to highest intensity reached*
I	*Instrumental:* detected only by seismographs		
		10	
II	*Feeble:* noticed only by sensitive people		3·5
		25	to
III	*Slight:* like the vibrations due to a passing lorry; felt by people at rest, especially on upper floors		4·2
		50	
IV	*Moderate:* felt by people while walking; rocking of loose objects, including standing vehicles		4·3
		100	to
V	*Rather Strong:* felt generally; most sleepers are awakened and bells ring		4·8
		250	
VI	*Strong:* trees sway and all suspended objects swing; damage by overturning and falling of loose objects		4·9–5·4
		500	
VII	*Very Strong:* general alarm; walls crack; plaster falls		5·5–6·1
		1000	
VIII	*Destructive:* car drivers seriously disturbed; masonry fissured; chimneys fall; poorly constructed buildings damaged		6·2
		2500	to
IX	*Ruinous:* some houses collapse where ground begins to crack, and pipes break open		6·9
		5000	
X	*Disastrous:* ground cracks badly; many buildings destroyed and railway lines bent; landslides on steep slopes		7–7·3
		7500	
XI	*Very Disastrous:* few buildings remain standing; bridges destroyed; all services (railways, pipes and cables) out of action; great landslides and floods		7·4–8·1
		9800	
XII	*Catastrophic:* total destruction; objects thrown into air; ground rises and falls in waves		>8·1 (maximum known, 8·9)

TABLE 4.9. The Modified Mercalli Scale of earthquake intensity. Diagram from Holmes (1978).

felt that seismic liquefaction is unlikely to present a serious problem during a large earthquake due to the coarse and relatively permeable nature of the gravels underlying low lying areas.

4.5 PROPOSED HAZARD ZONING APPROACH FOR THE WAIKAWA RESIDENTIAL AREA.

4.5.1 Current Land Use Zoning Practices for the Picton Region.

4.5.1.1 Picton Borough.

Land use zoning requirements for the Picton Borough are outlined in the Picton District Scheme (1981). The Scheme states that:

> "... for the purpose of determining whether any land is suitable for any particular use, regard shall be had to the best use of the land and its economic servicing and development, to earthquake fault lines, to liability to flooding, erosion or landslip to the stability of foundations, to traffic likely to be generated by the use, and to safety, health and amenities."

Land identified as being suitable for residential development is subdivided into residential zones A, B and S (see Picton District Scheme, 1981). These zones are defined primarily on the basis of ensuring the compatibility of land users rather than natural hazard avoidance. Professional site investigation are only required for sites where the slope angle exceeds 15° in any of these zones. In such cases, any application for building approval must be accompanied by:

> "... a certificate from a registered engineer (having a detailed knowledge of soil mechanics and slope stability) to the effect that the work proposed to be carried out will not be detrimental to the site itself or any adjoining site, and proper safegaurds have been employed to overcome the possible effect of slip, slump, erosion or landslide including proper provision for stormwater disposal."

The existence of a significant flooding hazard in the lower Waikawa stream catchment is acknowledged in the District Scheme, and new buildings in this area must conform to regulations governing minimum floor heights (see section 4.4.2).

The existing District Scheme is presently under review, as required under the Town and Country Planning Act, 1953 and 1977. The new Scheme is due to become operative later this year (1989). Land use zoning maps for the Picton Borough (Appendix 2) are reproduced from the current Pre-Review

Statement (a document outlining the objectives and policies the Council proposes to include in the forthcoming District Scheme). There may be some minor changes to these in the new District Scheme.

4.5.1.2 Marlborough County

Those parts of the study area outside the Picton Borough boundary fall under the jurisdiction of the Marlborough County Council, and are covered by the Marlborough District Scheme. The investigation requirements for individual building sites are essentially the same as those outlined in the Picton District Scheme mentioned above. The Marlborough District Scheme, however, contains the following additional requirement;

> "The construction of any building or accessory building or part thereof will not be permitted within 8 metres of the banks of any river, stream, drain, or watercourse or within any flood channel, without the consent of the Marlborough Catchment Board within areas subject to the Boards by-law No. 1, and outside such areas the consent of the Council shall be necessary."

The County Council has recently adopted code of practice for subdivision and land development (Marlborough County Council, 1988), which consists of the New Zealand Standards Association "Code of Practice for Urban Land Subdivision" (NZS 4404), with minor amendments. The document adopted by the County Council outlines the site investigation and design requirements for residential subdivisions in areas within the Marlborough County.

4.5.2 Hazard Zonation Approach.

The hazard mapping approach proposed for the Waikawa residential area (Figure 4.12) generally follows the first section of the conceptual outline illustrated in Figure 4.3 (i.e. the section covering the engineering geologists involvement). Geological hazard identification and assessment is based on a series of engineering geological investigations of both geological materials and the processes responsible for landscape development in the Picton area.

The engineering geological database includes the results of all field investigation and literature research already discussed, and is presented in the form of an engineering geological map of the Waikawa residential area at a scale of 1:5000 (Figure 4.1). Using this map as a plotting base

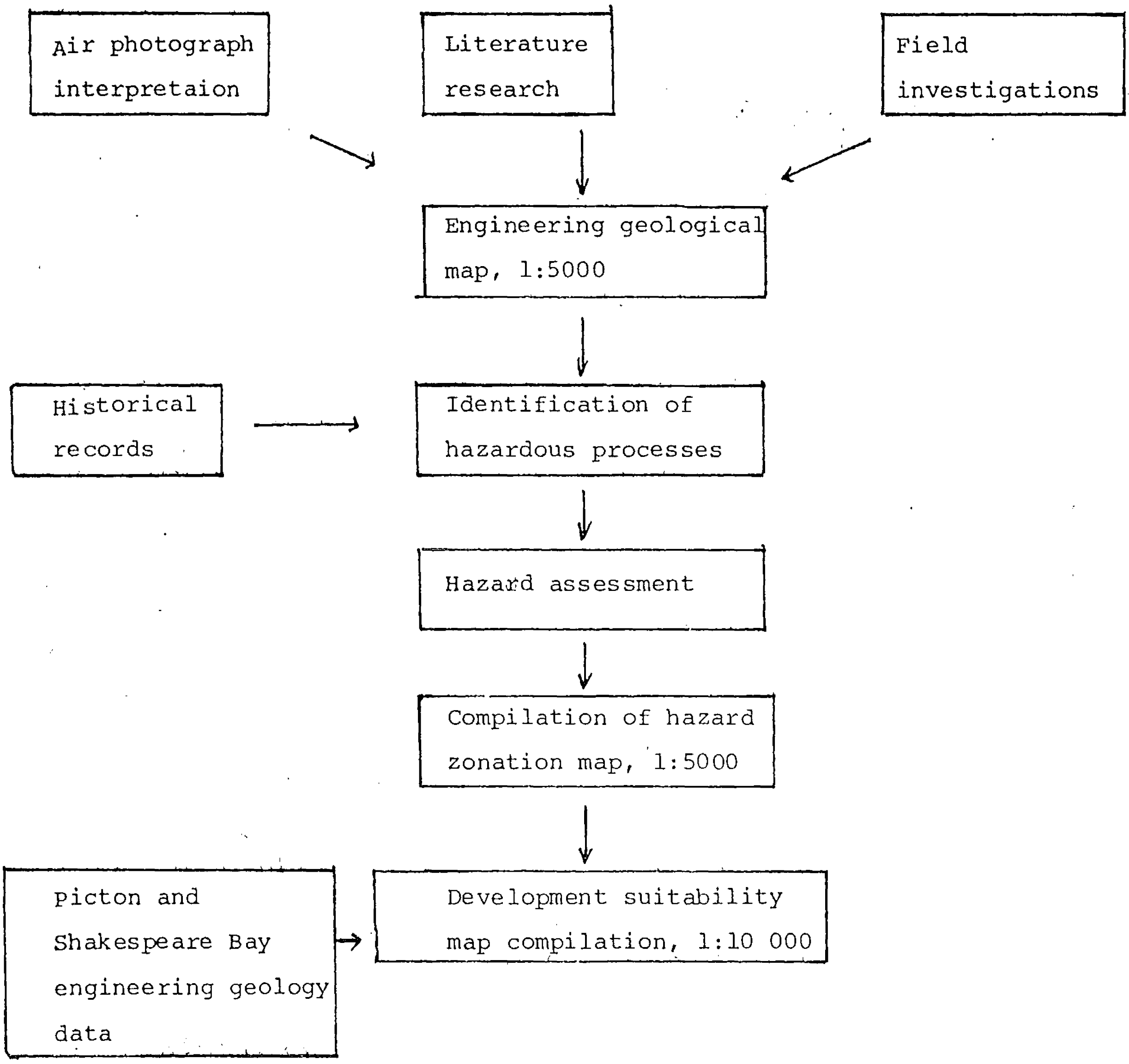


FIGURE 4.12. Flow chart outlining the conceptual approach to hazard zonation and mapping adopted by this study for the Picton region.

a hazard zonation map at the same scale has been compiled, indicating both the areas potentially affected by a given hazardous process, and the associated degree of hazard.

Finally, a development suitability map (Figure 4.2) has been compiled based on the above hazard map, and has been extended to cover the Picton and Shakespeare Bay areas at lesser detail. This map zones the area on the basis of future development potential, and as such is distinct from the hazard map, which illustrates the extent of hazardous processes presently affecting the Waikawa area, much of which is as yet undeveloped. The compilation and presentation of these maps is discussed in further detail below.

4.5.3 Engineering Geological Mapping

4.5.3.1 Methodology

The general mapping methodology followed in the course of the engineering geological investigation programme has already been discussed in chapter 3. The following comments apply specifically to the 1:5000 scale engineering geological map of the Waikawa residential area (Figure 3.2), with particular reference to it role in geological hazard zonation. The map was compiled primarily as a data source for a hazard zonation map of the same area, and as such was required to show all physical features related to the various hazardous processes identified in the area (sections 4.4.1 - 7). Areas subject to slope movement were identified with the aid of a series of aerial photographs spanning the last 30 years, with field verification where possible. It was therefore possible to make some determination of the relative age of individual landslide events, and a 4-fold age classification is employed based on the date of the most recent slope movement activity visible on air photographs. Each landslide feature is annotated with a alphanumeric code indicating both the date of last activity (1= <5 years, 2= 5 to 30 years, 3= >30 years, but surface expression suggests activity in historical times, and 4= obviously relict), and whether the slide has occurred in colluvium (C) or in-situ bedrock (R) (see Figure 3.2).

Also indicated on this map are active faults (seismic hazard), swamps (ground settlement hazard), major streams and associated floodplains (flooding, channel migration and siltation hazard), and alluvial debris fans (debris deposition hazard).

4.5.3.2 Data Presentation

In an effort to show the distribution of both geological materials and geomorphic surfaces, a 2-fold system of mapping units has been employed in the compilation of this map. Surface geology is shown by a series of graphic line symbols, which indicate the nature of the material only. A full description of each of these units is given in chapter 2. A second independent classification system utilises a series of colours to show both the age and mode of formation of the various geomorphic surfaces in the map area.

All the major maps compiled for this thesis are draughted on to base maps showing ridge lines (dotted), and streams (solid lines). This was considered sufficient to indicate the nature of the topography at the scales used. It was decided not to include either topographic contours or cadastral boundaries on these maps to avoid confusion.

4.5.3.3 Applications and Limitations

Engineering geological mapping at 1:5000 was undertaken with the primary objective of hazard zonation in mind. As such, this map is not intended as a substitute for site specific investigations. It is designed for use by land use planners as a guide to both expected foundation conditions, and to the likely site investigation requirements for the Picton area.

Dense vegetation and accessibility problems clearly restrict the amount of field checking possible when working in an area like Waikawa. Any map produced in such an area will be largely interpretive, and clearly mapping of the upper catchment areas will be of lesser reliability than is possible for the accessible lower catchments. Some caution is therefore necessary in using this map. The system of map symbols used includes an indication of the reliability of major features and boundaries.

4.5.3 Hazard Zonation Mapping

4.5.4.1 Methodology

The 1:5000 hazard zonation map of the Waikawa residential area (Figure 4.1, map pocket) aims to show the areal extent of all hazardous processes actually or potentially affecting the area in its present state. The outlines of features such as landslides, recent alluvial floodplains, swamps and debris fans were transferred directly from the engineering geological map to the hazard map, and were supplemented by both historical records of flood and landslide events, and field data concerning processes presently active (landsliding, coastal and stream bank erosion).

Estimates of the degree of hazard posed by these various processes are based on the age of most recent activity. In general the most recent activity falls in to either the 0-30 year period (the limit of air photograph coverage), the 30-100 year period (covered by historical records), and the greater than 100 year period (evidence preserved only in the geological record).
Clearly this approach is not ideal in all cases. For example, although landslides are more likely to occur at localities with a record of slope instability, first time failures may occur in other areas and for this reason all slopes in excess of 15° are defined as having some degree of landslide hazard. It is, however, felt that an system based on identification of existing and past problems is more relevant in this particular area than a system based principally on terrain classification, which would require considerably more data than is presently available to be effective.

Figure 4.13 outlines the definitions of each of the hazard zones shown on the map. Figure 4.14 presents a series of brief recommendations for further study and investigation for each hazard zone defined. These diagrams are also included on the hazard map itself.

4.5.4.2 Data Presentation

The extent of each individual hazard zone is shown with a dashed line, and are annotated with letter symbols corresponding to the particular

HAZARD ZONE DEFINITION

DEGREE OF HAZARD / PROCESS	SLOPE MOVEMENT L	FLOODING F	DEBRIS DEPOSITION D	STREAM BANK EROSION S	COASTAL EROSION C	GROUND SUBSIDENCE W
HIGH	Slope movements active during the last 30 yrs.	Areas liable to inundation in a 30 yr. period, assuming adequate preformance of existing flood protection works.	Areas liable to debris deposition, siltation, and channel migration in a 30 yr. period.	Sites of active removal of material at the stream bank within the last 30 yrs.	Sites of active removal of material at the shoreline within the last 30 yrs.	Areas of permanent ponded drainage. Potential ground subsidence hazard.
MODERATE	Slope movements showing no sign of activity during the last 30 yrs.	Areas liable to inundation in a 100 yr. period, assuming adequate preformance of existing flood protection works.	Areas liable to debris deposition, siltation, and channel migration in a 100 yr. period.	Insufficient data available to assign low and moderate hazard	Insufficient data available to assign low and moderate hazard	
LOW	Slope angle in excess of 15°, with no history of slope movement identified.	Areas liable to inundation in an extreme flood event, assuming failure of existing flood protection works.	Areas liable to debris deposition, siltation, and channel migration in an extreme rainfall event.			
NEGLIGIBLE	Slope angle less than 15°, with no history of slope movement identified.	No significant hazard	No significant hazard	No significant hazard	No significant hazard	No significant hazard
		Not shown on map				

FIGURE 4.13. Hazard zone definitions for hazard mapping in the Waikawa residential area.

DEVELOPMENT RECOMMENDATIONS

DEGREE OF HAZARD \ PROCESS	SLOPE MOVEMENT L	FLOODING F	DEBRIS DEPOSITION D	STREAM BANK EROSION S	COASTAL EROSION C	GROUND SUBSIDENCE W
HIGH	Extreme limitations. Development not recommended.	Extreme limitations. Development not recommended.	Extreme limitations. Development not recommended.	Development not recommended without certified engineering design of stream bank protection works.	Development not recommended without certified engineering design of coastal protection works.	Unsuitable for development without site de-watering and filling. Further investigation of ground subsidence potential required.
MODERATE	Significant limitations. Detailed site investigations required. Development may be possible on selected sites.	Significant limitations. Site investigation of flood hazard required. Protective measures and special foundation design may be reqd.	Significant limitations. Site investigation of debris and siltation hazard reqd. Culvert and watercourse design critical.	Insufficient data available to assign low and moderate hazard		
LOW	Some limitations. Engineering design of foundations and stormwater and effluent disposal required.	Some limitations. Generally favourable, but some assessment of flood hazard may be reqd. Stormwater control important.	Some limiatations. Generally favourable, but some assessment of debris and siltation hazard may be reqd. Culvert and watercourse design imp.			
NEGLIGIBLE	Suitable for residential development given normal engineering prudence, and compliance with local authority by-laws. Not shown on map					

FIGURE 4.14. Development recommendations for the hazard zones defined in Figure 4.13.

hazardous process affecting the area. The zone is coloured according to the degree of hazard assigned to the zone in question (see Figure 4.13). Hazardous processes affecting areas essentially linear in extent are shown as a dashed line between 2 triangular flags which are annotated and coloured in accordance with Figure 4.13. Localities where hazardous processes affect very small areas (for example very small landslides, tension crack development, gully scouring etc.) are shown with a single square flag, coloured and annotated as above.

Although no attempt at seismic hazard zonation is made, the position of the Late Quaternary trace of the Waikawa Fault is shown as the potential for fault reactivation does exist. As previously noted, seismic hazard evaluation is beyond the scope of this thesis.

4.5.4.3 Applications and Limitations

As stated earlier, the hazard zonation map indicates the problems currently being experienced in the Waikawa area, and does not attempt to predict the likely effects of future development. To use landsliding once again as an example, those areas defined on the map as being of low mass movement hazard in their present (natural) state may become unstable if high density residential development was undertaken. It is intended that this map will be used by land use planners and administrators to identify those areas affected by hazardous processes, the severity of the hazard, and to provide brief recommendations for further investigation in each case.

This system of combining both colour and letter symbols to indicate the nature of the process and the degree of hazard works well for the Waikawa area, but would be unsuitable for any area affected by 2 or more processes having different degrees of hazard. In such cases each individual process would have to be presented on an single factor hazard map. The use of a colour coding system does have significant advantages in clarity of presentation over the complex letter codes often adopted for such maps. This study adopts a "traffic light" colour coding, using red for the highest hazard level, orange for moderate hazard and green for low hazard.

As this map is derived from the engineering geological map (Figure 3.2), the same comments apply in terms of difficulty of access and minimal exposure limiting map reliability in some cases. It is however felt that the hazard map gives a useful representation of the hazardous geological processes active in the area.

4.5.5 Development Suitability Mapping

4.5.5.1 Methodology

A development suitability map (Figure 4.2, map pocket) covering the whole study area has been prepared at a scale of 1:10000, and represents the final stage in the hazard zonation processes. Assessment was based on the 1:5000 hazard map for the Waikawa area, and elsewhere on the 1:10000 engineering geology map, Figure 3.1. The development suitability map subdivides the whole study area into 4 development suitability classes which are based on the degree of geological and geotechnical limitations to urban development. This map differs from the hazard map in that it does not indicate the nature of the hazardous process imposing these limitations, but simply the degree of suitability for future urban development. Thus the 4 fold hazard zonation scheme adopted for the hazard map does not necessarily correspond to the 4 fold development suitability classification used in Figure 4.2.

The 4 development suitability classes are shown in Figure 4.15. Areas zoned class I are defined as being most suitable for development. These areas include much of the lower Picton and Waikawa catchment, some as yet undeveloped land in Boons Valley, and a number of ridge crests adjacent to presently developed areas. Class II land is characterised by low geotechnical limitations, and is generally suitable for development, although some further geotechnical assessment may be required. Those areas potentially affected by flooding or debris deposition in an extreme rainfall event fall into this class. Class III areas are characterised by moderate geotechnical limitations, and include all slopes in excess of 15°. Professional site-specific investigations are required, and special foundation design may be necessary. Investigations in many of the upper catchment areas to which this class was assigned were restricted to limited aerial photograph interpretation. Areas zoned as class IV have extreme geotechnical constraints, and are not generally considered developable. Limited development may be possible following detailed site specific investigation, but the cost of remedial works is likely to be prohibitive. Only those areas where active hazardous processes (i.e. those resulting in landscape modification in the past 10 years) are positively identified, or those areas known to be unsuitable for development from past experience are assigned this class.

While development suitability mapping in the Waikawa area is based on the hazard map, some boundaries have been adjusted to compensate for those areas presently free of major problems in their natural state, but potentially prone to landsliding if developed. Thus there is an element of subjectivity in the compilation of the development suitability map.

It was decided to extend development suitability mapping to cover the whole study area to give some indication of the areas outside of Waikawa that were, at the conclusion of this study, felt to be favourable sites for urban expansion. Clearly development suitability assessment for those areas outside the coverage of the 1:5000 maps is of lesser reliability, and contains a greater element of subjectivity. There is scope for further detailed mapping in these areas.

4.5.5.2 Data Presentation

The development suitability map is presented at a scale of 1:10000 on the same base map as the 1:10000 engineering geological map. The map does not show any geological or geomorphic features (other than ridge lines, streams, and roads), and zones the study area on the basis of the 4 development suitability classes as outlined in Figure 4.15.

4.5.5.3 Applications and Limitations

This map is intended primarily as an aid to land use planning at the scale at which it is presented. It is in no way designed as a substitute for proper engineering site investigations. The map identifies those areas most suitable for future development from a geotechnical point of view only, and does not take into account other determining factors, such as environmental considerations or the compatibility of users. This map is not intended to be used as a land use zoning map per se, but as one of several inputs to the land use planning process.

DEVELOPMENT SUITABILITY CLASSES

□	CLASS IV	EXTREME GEOTECHNICAL LIMITATIONS GENERALLY UNSUITABLE FOR DEVELOPMENT
□	CLASS III	MODERATE GEOTECHNICAL LIMITATIONS SUITABLE FOR DEVELOPMENT ONLY AFTER DETAILED GEOTECHNICAL SITE INVESTIGATIONS
□	CLASS II	LOW GEOTECHNICAL LIMITATIONS GENERALLY SUITABLE FOR DEVELOPMENT, ALTHOUGH SOME GEOTECHNICAL INVESTIGATIONS MAY BE REQUIRED
□	CLASS I	NO SIGNIFICANT GEOTECHNICAL LIMITATIONS SUITABLE FOR DEVELOPMENT

FIGURE 4.15. The 4 development suitability classes used in development suitability mapping of the whole study area.

As mentioned earlier, the Picton and Shakespeare Bay regions have not been assessed at the same detail as the Waikawa Bay area, and as such the information presented for these areas may not be of the same reliability.

4.5.6 Comparison with Existing Hazard Zonation Practices.

Unlike a number of the hazard zonation systems proposed in section 4.3, the approach adopted by this study does not require sophisticated computer analysis, has been completed at a minimum of cost. The initial investigation methods do not require expensive equipment or detailed laboratory testing, and this approach is therefore ideally suited for use in areas where more complex methods are not warranted on economic grounds.

At the scale of this study (1:5000-1:10000), it is felt that a system based entirely on a standard terrain classification scheme would be too rigid. Engineering geological input is important in assessing the role of active physical processes in landscape formation, and therefore hazard assessment. The use of existing information in the form of historical accounts and knowledge of local residents is also important, particularly in areas where there is no systematic recording of the occurrence of hazardous events.

The maps produced by this study may be compared with the G.A.S.P. programme currently in use by the Geotechnical Control Office, Hong Kong (see section 4.3.1). While the resources available for this study are not comparable to the G.A.S.P. programme, the conceptual approach adopted by this study represents a simplification of the GASP approach. The engineering geological map (Figure 3.2) represents the initial database, and is thus a combination of the terrain classification and physical factor maps used in Hong Kong. The hazard zonation map is equivalent to the physical constraints map, in that both define the type of hazardous processes affecting particular area. The development suitability map (Figure 4.2) is paralleled with the Geotechnical Land Use Maps (GLUM) of GASP, both zonning the map area in terms of 4 classes based on the overall geotechnical constraints to future development.

In comparison with the ULUC surveys (see section 4.3.5), the approach outlined in this study is vastly simpler, while still dealing with the critical question of identification and modeling of hazardous processes. As such this approach would be feasible in areas where a ULUC survey would not be economically justifiable.

It is also felt that the ULUC system is better suited to larger scale application (i.e. 1:20000 or greater), and the use of exactly the same system at scales less than 1:5000 is questioned. The PUCE and ZERMOS systems work at scales of 1:20000-1:25000, and, like the ULUC surveys, are based heavily on terrain classification. To be effective, the use of terrain classification techniques at scales of 1:5000 or less must be accompanied by sound engineering geological and geotechnical information. This is the basis of the successful GASP programme in Hong Kong, which uses both terrain classification and engineering geological mapping as a basis for assessing development potential.

Comparison with the more regional systems of hazard zonation described in section (PUCE, ZERMOS, and regional slope stability mapping in California) is not practical, as these all cover considerably larger areas than this study. When dealing with scales in excess of 1:20 000, the use of standardised terrain classification schemes based heavily on remote sensing becomes more efficient in terms of time and cost. There still, however, exists a need for some form of engineering geological input before final planning decisions are made based on maps derived in this way.

4.5.6 Future Recommendations.

The major factor limiting the accuracy of hazard assessment in the Picton-Waikawa area is the lack of basic data. Prior to this study the only geological and pedological maps covering the area were 1:250000 sheets, and are therefore wholly unsuitable for application at the scale of this study (i.e. 1:5000-1:10000). The engineering geological mapping of this study represents the first attempt at systematic mapping of the study area for the purposes of hazard assessment and planning input. It is therefore envisaged that these maps may be refined as additional data becomes available in the course of future site investigations.

Historical recording of the occurrence of hazardous events in the study area has been minimal, which makes hazard assessment difficult. It is recommended that systematic records of all hazardous events occurring in the region be kept, particularly in the case of slope instability.

Since almost all the hazardous processes occurring in the study area are initiated by sustained or intense rainfall episodes, there is a need for an improved climatological database. Although there are several rain gauges instaled in the residential areas of both Picton and Waikawa, there is a need for further rainfall data from the upper catchment areas. Given such a database, it is possible to calculate return periods for various magnitude events with considerably greater reliability than is possible at present. Similarly, improved rainfall data and recording of mass movement occurrence would allow further investigation of soil moisture threshold values for the onset of landsliding.

Further investigations of the hydrological parameters of the major catchments of the study area is also important. Stream gaugings during high intensity rainfall events could be used in conjunction with rainfall data to estimate catchment response to various magnitude rainfall events. This data could then be used to provide a much needed indication of the magnitude-frequency relationships for flood events, which is a necessary input to culvert and watercourse design.

Further investigation of the activity of the Waikawa Fault requires further absolute age control on the Late Quaternary development of the Waikawa area. It is hoped that Carbon 14 dating of wood fragments found beneath the W_4 alluvial surface (where tectonic disturbance of gravels is observed) will constrain the age of this activity. Trenching across the fault trace may also provided further information on the age, sense and magnitude of Late Quaternary fault movement.

Clearly a computer based system of information storage and retrieval would be readily suited to management of both geotechnical and climatological databases.

4.6. SYNTHESIS.

A number of hazardous geological processes have played an active part in the Late Quaternary geomorphic development of Picton, Waikawa and Shakespeare Bay areas, and continue to represent a threat to urban development in places. A hazard zonation map has been compiled based on an engineering geological assessment of the Waikawa residential area, identifying those areas potentially at risk from hazardous processes. On the basis of this information a development suitability map has been prepared outlining those areas most suitable for future development from a geotechnical point of view, and those areas considered unsuited to further development due to geotechnical constraints. It is intended that this information will be used by local authorities as an input to the land use planning and land managment process.

CHAPTER 5
SUMMARY AND CONCLUSIONS

5.1 STUDY BACKGROUND.

Continued residential development in the Picton area, particularly at Waikawa Bay, has highlighted the need for more geotechnical information as an input to the land use planning process. Previous work in the area has tended to be very large scale (for example 1:250000 geological and pedological mapping), or site specific (for example civil engineering site reports for individual properties, at scales of 1:1000-1:500). This project covers the Picton, Waikawa and Shakespeare Bay areas at scales of 1:5000-1:10000, which are felt to be most appropriate for the identification of features relevant to close residential subdivision and development.

This thesis project was initiated to provide information on (i) expected foundation materials and conditions, and (ii) the nature and extent of geological processes with the potential to affect urban development. Engineering geological maps have been prepared from air photograph analysis and field investigation, and models have been developed for a number of hazardous processes active or potentially active in the study area. On the basis of this information a hazard map of the Waikawa residential area has been compiled showing areas potentially at risk from hazardous processes, and the associated degree of hazard. Finally, a development suitability map was compiled for the whole study area, and indicates areas where extreme geotechnical limitations severely restrict future development, as well as outlining those areas most suited to future urban development form a geotechnical point of view.

It is intended that the results of this thesis will provide interested local authorities with geotechnical information at a level of detail not previously available, and with which urban development in the Picton region may be adequately controlled.

5.2 Geology and Geomorphology.

The upper catchment areas of Picton, Waikawa and Shakespeare Bay consist of steep, densely vegetated slopes and deeply incised gullies, with the orientation of major valleys and ridges strongly influenced by a regional NNW-SSE tectonic alignment. The lower catchment areas of Picton and Waikawa are infilled with alluvial fan and floodplain gravels, forming large areas of relatively flat land. The geomorphic development of the study area is closely related to climatic fluctuations and associated sea level changes throughout the Quaternary Period. The Marlborough Sounds are considered to represent a system of river valleys drowned as a result of the Postglacial rise in sea level. While the Sounds show no evidence of actual glaciation, the effects of a periglacial climate prevailing during colder periods are observed in the form of relict scree deposits, and stranded alluvial surfaces formed at times of greater sediment supply.

The study area is underlain by Marlborough Schist to the west, and Pelorus Group greywackes and argillites to the east. A small area of Tertiary marginal marine sedimentary rocks underlie the head of Shakespeare Bay, and are thought to represent a remnant of once widespread Oligocene aged sedimentary basin deposits. All bedrock units are complexly jointed and fractured, and are weathered to grades III-IV on steeper slopes, and to grades V and VI on more gentle lower slopes.

The surficial geology of the upper catchment areas consists predominantly of a 1-2 metre veneer of bedrock colluvium, while the flatter bedrock surfaces in the lower catchments are overlain by regolith profiles formed by in-situ weathering of the underlying bedrock. The majority of the lower catchment areas consist of coarse, poorly sorted Late Otiran to Early Holocene alluvial floodplain gravels, and a series of extensive alluvial debris fans of similar age extend from stream catchments on the eastern side of Waikawa. Landslide deposits are also identified on many of the steeper slopes, and a large fan consisting of reworked angular mass movement debris is observed on the western side of Shakespeare Bay.

5.3 Engineering Geological Investigations

5.3.1 Methodology.

Engineering geological investigations for this thesis consisted of engineering geological mapping (1:5000-1:10000), site specific field investigations and sampling (1:50-1:1250), and laboratory geotechnical characterisation of materials. Engineering geological mapping was carried out using both aerial photograph interpretation and field mapping techniques. Field investigation methods included hand augering, exposure logging, penetrometer testing and shallow seismic refraction profiling, all of which are relatively cheap and portable techniques, and give adequate information on subsurface materials and conditions in most cases. Laboratory techniques employed for analysis of soil material included Atterberg limit determination, grainsize analysis by sieve and hydrometer methods, x-ray diffraction identification of clay minerals, and natural water content determination. Rock strength testing by point load and cone indenter methods was also conducted for weathered greywacke bedrock samples.

5.3.2 Laboratory Investigations

10 representative samples of greywacke colluvium and regolith were collected throughout the Waikawa area, and were subjected to laboratory testing to determine Atterberg consistency limits, grain size distribution, water content, and clay mineralogy. The purpose of this testing programme was to provide a general geotechnical characterisation of the physical properties of weathered greywacke for the study area, rather than attempting any detailed investigation of soil behaviour. In general, greywacke regolith and colluvial matrix material may be classified as either inactive silts or clays of low to medium plasticity, with kaolinite as the predominant clay mineral. Ten samples of weathered greywacke bedrock were tested for rock strength by both point load and cone indenter methods. Unconfined compressive strength values determined from the point load method ranged from 2.53 to 10.15 MPa, while the cone indenter test yielded values of 23.17 to 118.6 MPa. The low values obtained from the point load test were due to the pervasively fractured nature of the samples used. The disagreement between these 2 sets of values suggests that the results of each test should be used independently as relative indices of rock strength.

5.3.3 Field Investigations

Field investigations were carried out at a site specific scale primarily to develop models for various active processes identified in the study area. Individual studies were made of slope instability on the eastern side of Shakespeare Bay, bedrock weathering profiles at the Jeffcott subdivision, and active faulting and alluvial deposition in the lower Waikawa stream catchment.

Failure models for landslides in colluvium, bedrock, and cut slopes were formulated from investigations in Shakespeare Bay and at Waikawa. Landslides in colluvium usually take the form of debris slide flows, and are triggered by high intensity rainfall episodes. Rainfall infiltrates through tension and desiccation cracks, and appears to result in high soil moisture levels in a 0.5 to 1 metre zone approximately 2-3 metres below the ground surface. Water pressures build up at this depth, resulting in a loss of soil shear strength and failure. The bedrock/colluvium interface only acts as a failure surface if it occurs within this zone.

Failures in greywacke bedrock, both in natural ground and cut slopes, occur as a result of high crack water pressures within the jointed rock mass. Slope failure generally takes place along unfavourably oriented joints, resulting in multiple wedge slides.

The results of all of the above investigations also provided field information useful in the compilation of the 1:5000 and 1:10000 engineering geological maps.

Exposure logging and sampling at the Jeffcott subdivision Waikawa showed that steep greywacke slopes consist of 1-2 metres of poorly sorted angular colluvium sharply overlying a highly weathered bedrock surface. This highly weathered zone persists 1.5-2 metres into the rock, where there is a 1-2 metre transition to moderately weathered rock. On gentler slopes (<10°) greywacke bedrock is weathered in-situ to grade V-VI (regolith).

Investigation of the extensive alluvial deposits in the lower Waikawa Stream catchment suggest that the majority of this material was deposited in Late Otiran-Early Holocene times. Subsequent Mid-Late Holocene fluvial incision has resulted in the flight of river terraces observed today.

A Late Quaternary trace of the Waikawa Fault is observed on the eastern side of the Waikawa residential area, and associated seismic deformation is observed in Late Holocene alluvial gravels. It is therefore inferred that their has been seismic activity associated with the fault zone within the last 5000 years

5.3.4 Engineering Geological Mapping.

Engineering geological mapping was undertaken for the whole study area (1:10000), and in greater detail (1:5000) for the Waikawa residential area. It was decided to adopt this dual scale approach as a compromise between the need to provide information for the whole study area, and the high degree of mapping detail required for the subsequent compilation of a hazard zonation map for the Waikawa area. The Waikawa residential area was selected for more detailed study as it is the primary site of urban expansion in the study area at present.
It is therefore intended that having developed a workable mapping approach for Waikawa, this may be extended at a later date to cover the Picton Shakespeare Bay areas with a similar degree of detail. Mapping methodology consisted of identification of important features through air photograph analysis, and subsequent field checking where terrain allowed. Clearly much of the upper catchments are inaccessible and densely vegetated, and detailed mapping has not been attempted for these areas. These maps give a reliable indication of the engineering geology of the study area at the scales used, although their direct application to smaller scale site investigation requires caution.

5.4 Hazard Assessment.

A wide variety of approaches to the problem of geological hazard assessment and hazard/risk zonation have been employed internationally, and these vary according to the scale of investigation. Various systems of terrain analysis involving classification of the land surface on the basis of a standardised list of physical attributes are also widely used. This type of approach has the advantage that much of the required data may be collected by remote sensing (primarily air photographs), and by using existing information. While terrain classification is a useful technique of data collection and presentation, there exists a need for some form of engineering geological input regarding the nature the active geological processes affecting the area in question.

The hazard zonation approach proposed in this study is essentially based on an engineering geological assessment of the study area. Investigation and modelling of active processes, combined with engineering geological mapping forms a database from which hazardous processes may be identified, delineated, and their degree of hazard assessed.

The areal extent of hazardous processes is determined directly from engineering geological mapping, and the degree of hazard assessed on the basis of the date of most recent activity. The hazard map for the Waikawa residential area indicates those areas affected or potentially affected by a range of different processes, and provides a colour code indicating the assessed degree of hazard. This map does not attempt to zone on the basis of the potential "risk" (i.e. expected degree of loss) to urban development, which depends on future land use, but rather identifies hazardous processes, and assesses the probability of occurrence of a hazardous event.

On the basis of the above information, a development suitability map is compiled showing the degree of geotechnical limitations to future development. This map also incorporates an element of subjectivity in areas where assessment of development potential is difficult due to limited data. This map deals only with geotechnical limitations to urban development, and does not take into account other factors such as land user compatibility or environmental considerations. As such it is intended not as a land use planning map per se, but as an input to the land use planning and land management process.

5.5 Recommendations.

5.5.1 Hazard Assessment and Land Use Planning.

The engineering geological approach adopted in this thesis is considered to be readily suited to hazard assessment in the study area. The recommendations for site investigation requirements and development suitability are outlined on the maps themselves (Figures 4.1 and 4.2). It is recommended that this approach be extended to cover the Picton and

Shakespeare Bay areas at the 1:5000 scale, and possibly to other areas of the Marlborough Sounds. Similarly, as more data comes to hand, the maps completed for this thesis may be checked and refined.

The identification of hazardous processes prior to the granting of planning consent for urban development projects is of vital importance given the geotechnical setting of the study area. It is intended that the results of this thesis will contribute to the continued safety of urban development the Picton, Waikawa and Shakespeare Bay catchments.

5.5.2 Further Geotechnical Investigations

At the conclusion of this study the following recommendations are made for further geotechnical studies.

(i) Soil strength parameter determination by tri-axial or shear box testing of weathered greywacke regolith (weathering grades V and VI) and colluvium would be useful for site specific stability calculations. The investigation of the effect of soil moisture content on strength parameters may assist in the identification of a threshold soil moisture value for the occurrence of landsliding.

(ii) Any new exposures (road cuttings, foundation excavations etc.) should be photographed and preferably logged soon after excavation.

(iii) Any fossil carbonaceous material (charcoal, wood etc.) should be carefully collected and the locality described. Dating of such material could provide some age control on the geomorphic evolution of the study area, which is presently lacking. Such information may be important in assessing the age and return period of a particular hazardous process.

(iv) There is scope for further geotechnical characterisation of different bedrock weathering grades to extend the results of this study.

(v) Some form of rationalised data storage and retrieval system for geotechnical information should exist for the study area. Such a database should be accessible to all interested parties, and would be readily suited to computerised data management.

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APPENDIX 1.

Engineering geological description schedules for rock and soil material
(from Bell and Pettinga, 1984)

ENGINEERING GEOLOGICAL FIELD DESCRIPTION FOR ROCK MATERIAL

WEATHERING

	TERM	GRADE	ROCK DESCRIPTION
6.	* residual soil (RW)	VI	discolouration and complete transformation to soil; original fabric destroyed
5.	completely weathered (CW)	V	discolouration and transformation to soil; original fabric largely preserved
4.	highly weathered (HW)	IV	material pervasively altered with discolouration and loss of strength; fabric preserved; lithorelicts
3.	moderately weathered (MW)	III	penetrative discolouration and alteration of rock material, with some loss of strength
2.	slightly weathered (SW)	II	slight discolouration of rock fabric; no loss of material strength
1.	unweathered (UW)	I	no discolouration or loss of strength, or any other effects due to weathering

STRENGTH

	TERM	POINT LOAD STRENGTH INDEX Is(50)	FIELD ESTIMATION OF STRENGTH
1.	extremely strong (ES)	more than 10	can only be chipped with geological hammer
2.	very strong (VS)	3 to 10	several hard blows required to break hand specimen
3.	strong (S)	1 to 3	few firm blows of hammer required to break specimen
4.	moderately strong (MS)	0·3 to 1	breaks readily with one blow of hammer
5.	moderately weak (MWk)	0·1 to 0·3	broken by hand only with difficulty; small thin pieces broken by finger pressure
6.	weak (Wk)	0·03 to 0·1	broken by hand; pieces 25 mm or more broken by finger pressure
7.	* very weak (VWk)	less than 0·03	crushed or remoulded by hand (grades into soil materials)

* may require description as soil material

GEOLOGICAL CLASSIFICATION

CRYSTAL OR GRAIN SIZE (mm)	SEDIMENTARY (†) CLASTIC	SEDIMENTARY (†) CHEM/ORGANIC	Mode of Occurrence	IGNEOUS (†) Silicic	IGNEOUS (†) Intermed.	IGNEOUS (†) Mafic	IGNEOUS (†) Ultramaf.	METAMORPHIC (†) FOLIATED	METAMORPHIC (†) MASSIVE
very coarse — 64 — coarse — 2	CONGLOMERATE (1), AGGLOMERATE (2), BRECCIA (3)		INTRUSIVE	GRANITE (27), GRANODIORITE (28)	SYENITE (29), DIORITE (30)	GABBRO (31)	PERIDOTITE (32), DUNITE (33)	GNEISS (34), SCHIST (35)	HORNFELS (39), MARBLE (40)
medium — 0·06	SANDSTONE (4)	Calcareous: LIMESTONE (9); Siliceous: CHERT (10), OTHER (11)						PHYLLITE (36)	QUARTZITE (41)
fine	TUFFS (7): SILTSTONE (5), MUDSTONE (6)	Carbonaceous: COAL (12), OTHER (13); Ferruginous: LATERITE (14), OTHER (15)	EXTRUSIVE	RHYOLITE (19), OBSIDIAN (20), DACITE (21)	TRACHYTE (22), ANDESITE (23)	DOLERITE (24), BASALT (25)	SERPENTINITE (26)	SLATE (37)	AMPHIBOLITE (42)
very fine — 0·002	CLAYSTONE (8)	Saline: ROCK SALT (16), GYPSITE (17), OTHER (18)						MYLONITE (38)	(†) OTHERS: Specify (43)

[ ] ---	WEATHERING TERM	[ ] ---	STRENGTH TERM	[ ] [ ] [ ] --- --- ---	COLOUR	[ ] ---	FABRIC	[ ] [ ] --- ---	ROCK NAME

COLOUR

1: light	1: pinkish	1: pink
2: dark	2: reddish	2: red
	3: yellowish	3: yellow
	4: brownish	4: brown
	5: olive	5: olive
	6: greenish	6: green
	7: bluish	7: blue
	8: whitish	8: white
	9: greyish	9: grey
		0: black

FABRIC

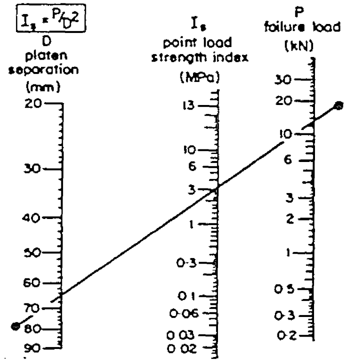
1: finely layered (< 25 mm)

2: coarsely layered (25 - 100 mm)

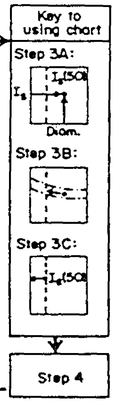
3. massive

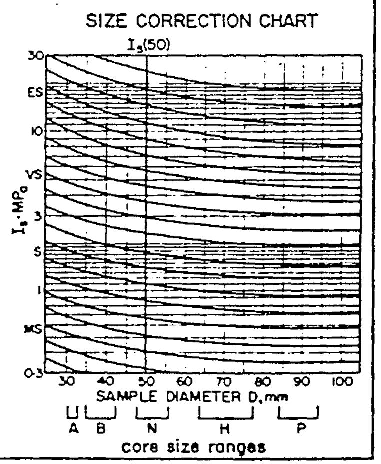
4. other (specify)

POINT LOAD STRENGTH INDEX



USE OF NOMOGRAM:
Step 1: D = 65·5 mm; P = 13·0 kN
Step 2: I_s = 3·1 MPa
Step 3: Using size correction chart I_s (50) = 3·6 MPa
Step 4: Strength designation 'Very Strong'





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ENGINEERING GEOLOGICAL FIELD DESCRIPTION FOR SOIL MATERIAL

WEATHERING

	TERM	GRADE	SOIL DESCRIPTION
5	Completely Weathered (CW)	V	completely discoloured and altered, no trace of original fabric
4	Highly Weathered (HW)	IV	mostly altered and weakened, little trace of original fabric
3	Moderately Weathered (MW)	III	large discoloured portions of original soil separated by more altered material, significantly weakened
2	Slightly Weathered (SW)	II	minor discolouration of some parts of the original soil, no loss of strength
1	Unweathered (UW)	I	original soil with NO discolouration, loss of strength or other effects due to weathering
0	NOTE in coarse-grained soils record weathering grade of DOMINANT fraction here and qualify ✱ weathering grade of subordinate and/or minor fractions if appropriate		

STRENGTH

	TERM	FIELD CRITERIA
1	loose	can be removed from exposure in disaggregated form by hand
2	compact	only removed from exposure by implement; material readily disaggregated by physical means
3	+ cemented	only removed from exposure by implement; material does not disaggregate
4	hard	may be removed from exposure with difficulty by implement or hand; softened on immersion in water and may be remoulded
5	stiff	indented by thumb pressure, but not moulded by fingers; softened on immersion in water, and may be remoulded
6	firm	moulded or indented only by strong finger pressure; easily moulded after immersion in water
7	soft	easily indented or moulded by finger pressure
8	very soft	exudes between fingers when squeezed
9	spongy	readily compressed by finger pressure, but cannot be remoulded

+ may require description as rock material

UNIFIED SOIL CLASSIFICATION SYSTEM

FIELD IDENTIFICATION						GROUP SYMBOL	TYPICAL NAMES
COARSE-GRAINED SOILS	GRAVELS (<50% larger than 2mm)	clean gravels	wide range in grain size and substantial amounts of all interm. sizes			GW	well graded GRAVELS
			predom. one size or a range of sizes with some interm. sizes missing			GP	poorly graded GRAVELS
		gravels with fines	non-plastic fines (see ML below)			GM	poorly graded SILTY-GRAVELS
			plastic fines (see CL below)			GC	poorly graded CLAYEY-GRAVELS
	SANDS (<50% smaller than 2mm)	clean sands	wide range in grain sizes and substantial amounts of all interm. sizes			SW	well graded SANDS
			predom. one size or a range of sizes with some interm. sizes missing			SP	poorly graded SANDS
		sands with fines	non-plastic fines (see ML below)			SM	poorly graded SILTY-SANDS
			plastic fines (see CL below)			SC	poorly graded CLAYEY-SANDS
			SHINE	DILATANCY (1)	TOUGHNESS (1)		
FINE-GRAINED SOIL	SILTS AND CLAYS	LIQUID LIMIT <50	none to very dull	quick to slow	none	ML	INORGANIC SILTS with slight plasticity
			moderate	none to very slow	medium	CL	INORGANIC CLAYS of low to medium plasticity
			none to very dull	slow	slight	OL	ORGANIC SILTS & CLAYS of low plasticity
		LIQUID LIMIT >50	dull	slow to none	slight to medium	MH	INORGANIC SILTS of high plasticity
			very glossy	none	high	CH	INORGANIC CLAYS of high plasticity
			moderate to v. glossy	none to very slow	slight to medium	OH	ORGANIC CLAYS of medium to high plasticity
HIGHLY ORGANIC SOILS			identified by colour, odour, spongy feel and fibrous texture			Pt	PEAT and other highly organic soils

PROCEDURES FOR FINE-GRAINED SOILS OR FRACTIONS (1)

DILATANCY (reaction to shaking) -

1) Prepare pat of moist soil, adding water to make soft - but not sticky.

2) Place pat in palm of hand, shake horizontally by striking vigorously against other hand

Positive Reaction: appearance of water on surface of pat, which becomes glossy. When squeezed between fingers, water and gloss disappear, pat stiffens and may crumble

TOUGHNESS: (consistency near plastic limit):-

1) Mould sample to consistency of putty, adding water or air drying as required.

2) Roll to thin (3mm) thread, fold and reroll repeatedly until thread crumbles at plastic limit

3) Knead together and continue until lump crumbles.

Diagnosis: a tough thread and stiff lump indicate high plasticity; a weak thread and lump low plasticity clays.

GROUP SYMBOL CODINGS FOR USCS

COLUMN 1		COLUMN 2	
G:1	C:4	W:1	C:4
S:2	O:5	P:2	L:5
M:3	Pt:6	M:3	H:6

BOUNDARY CLASSIFICATIONS specify, enter 0,0

--- ---	WEATHERING TERM	---	WATER CONTENT TERM	---	STRENGTH TERM	--- --- ---	COLOUR	---	FABRIC	--- --- ---	SOIL NAME	--- ---	USCS SYMBOL

WATER CONTENT

	TERM	FIELD CRITERIA
1	Dry	looks and feels dry; fine-grained soils usually hard, powdery or friable; coarse-grained soils may run freely through hands
2	Moist	soil feels cool and may be darkened in colour, particles tend to adhere in coarse-grained materials, fine-grained soils may be softened
3	Wet	soils feel cold and are darkened in colour, free water forms on hands when sample is disturbed
4	Saturated	restricted to wet soils below the water table or the static water level in excavations or drill holes

COLOUR

1: light	1 pinkish	1 pink
2: dark	2 reddish	2 red
	3 yellowish	3 yellow
	4 brownish	4 brown
	5 olive	5 olive
	6 greenish	6 green
	7 bluish	7 blue
	8 whitish	8 white
	9 greyish	9 grey
		0 black

FABRIC

1: finely layered (<25 mm)
2: coarsely layered (25-100mm)
3: massive
4: other (specify)

SOIL NAME

✱SUBORDINATE FRACTION — 20-50% volume visual estimate

DOMINANT FRACTION — >50% volume visual estimate

✱ MINOR FRACTION — < 20% volume visual estimate

Subordinate fraction

1	coarse	gravelly
2	medium	gravelly
3	fine	gravelly
4	coarse	sandy
5	medium	sandy
6	fine	sandy
7	silty	
8	clayey	
9	peaty	

PARTICLE SIZE

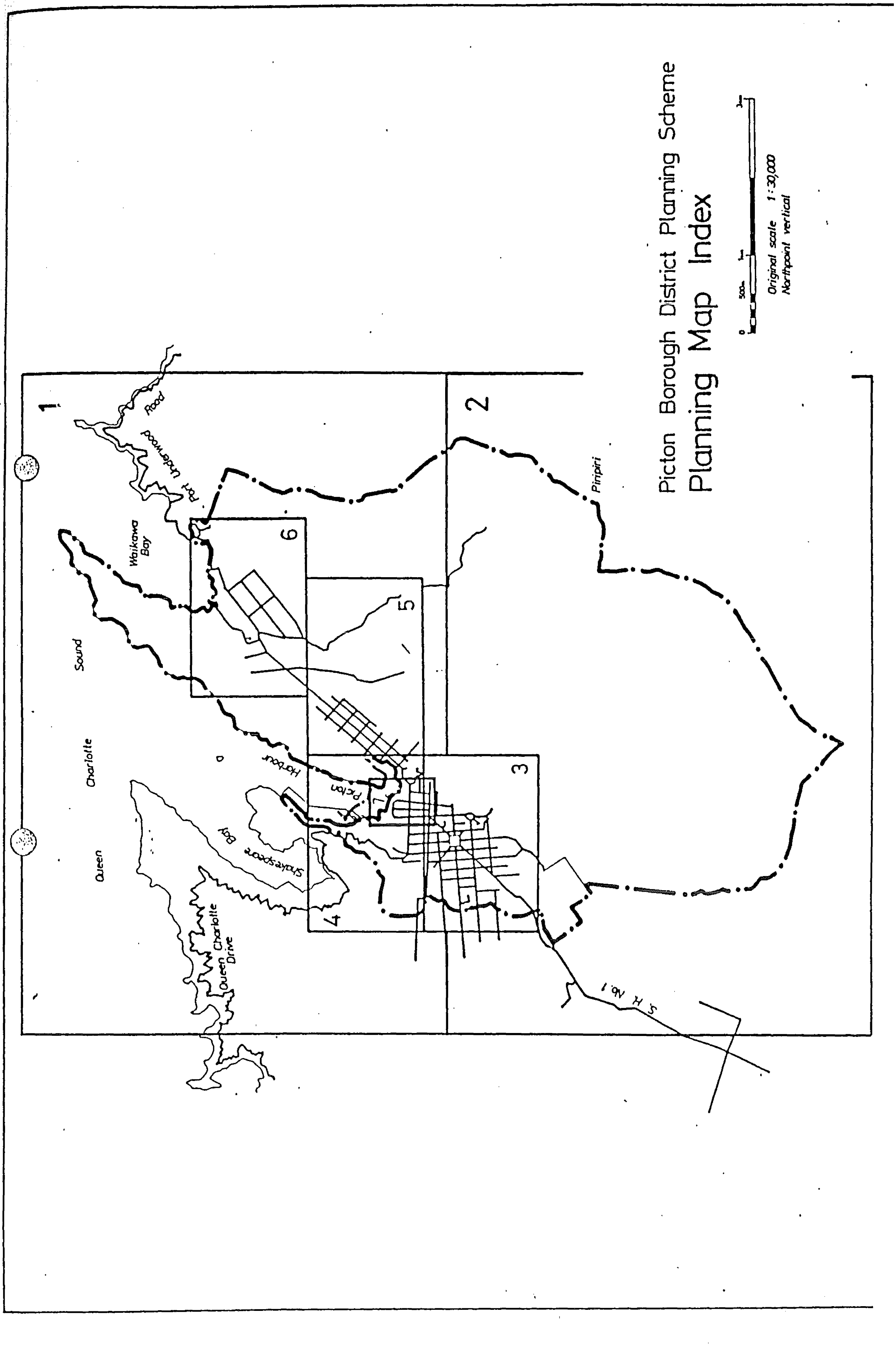
SOIL TYPE TERM		PARTICLE SIZE (mm)	GRAPHIC LOG
1 coarse	gravel	> 60	
2 medium	gravel	20-60	
3 fine	gravel	2-20	
4 coarse	sand	0.6-2.0	
5 medium	sand	0.2-0.6	
6 fine	sand	0.06-0.2	
7 silt		0.002-0.06	
8 clay		< 0.002	
9 peat		NA	

Minor fraction

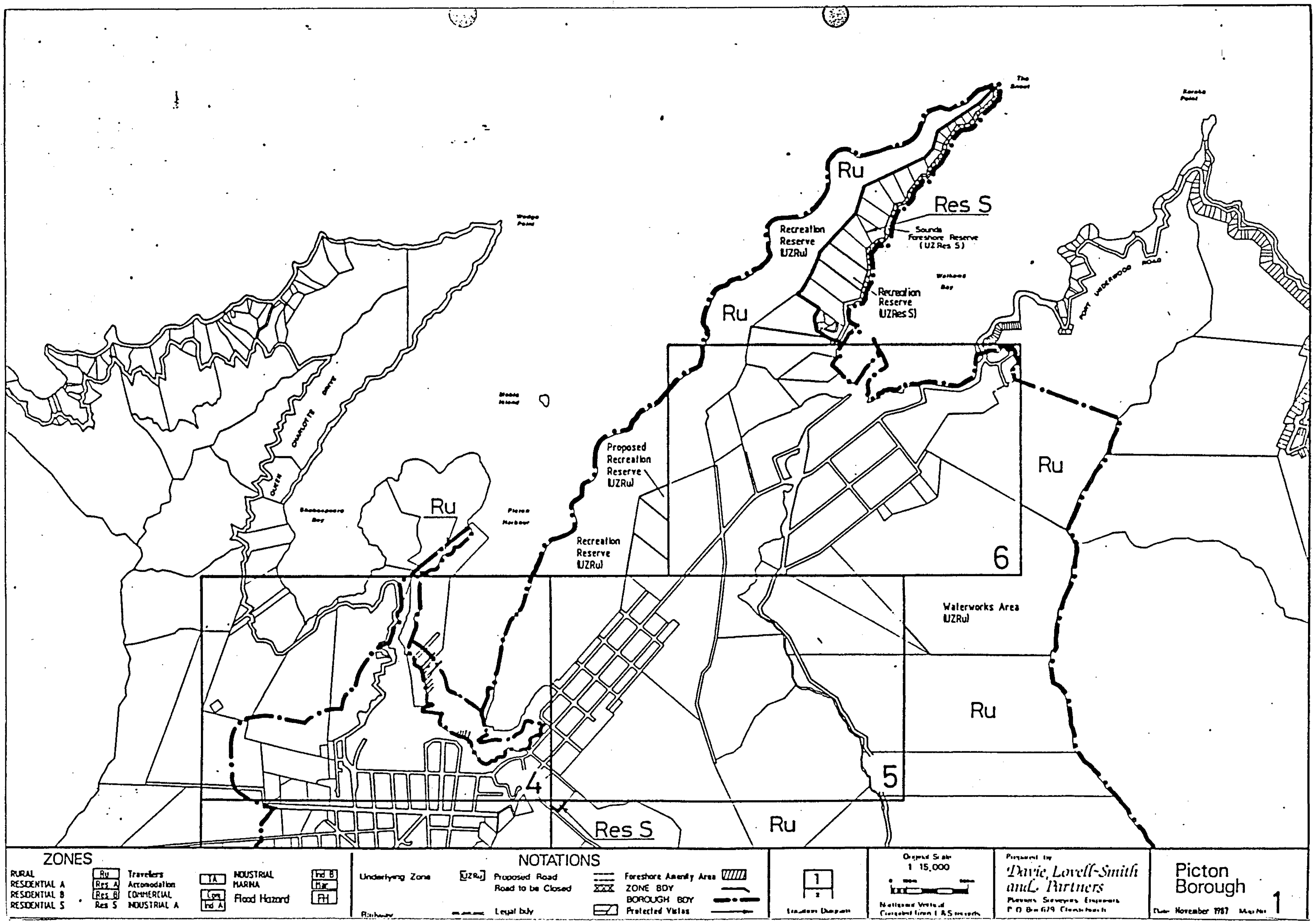
WITH SOME			
	1	coarse	gravel
	2	medium	gravel
	3	fine	gravel
	4	coarse	sand
	5	medium	sand
	6	fine	sand
	7	silt	
	8	clay	
	9	peat	

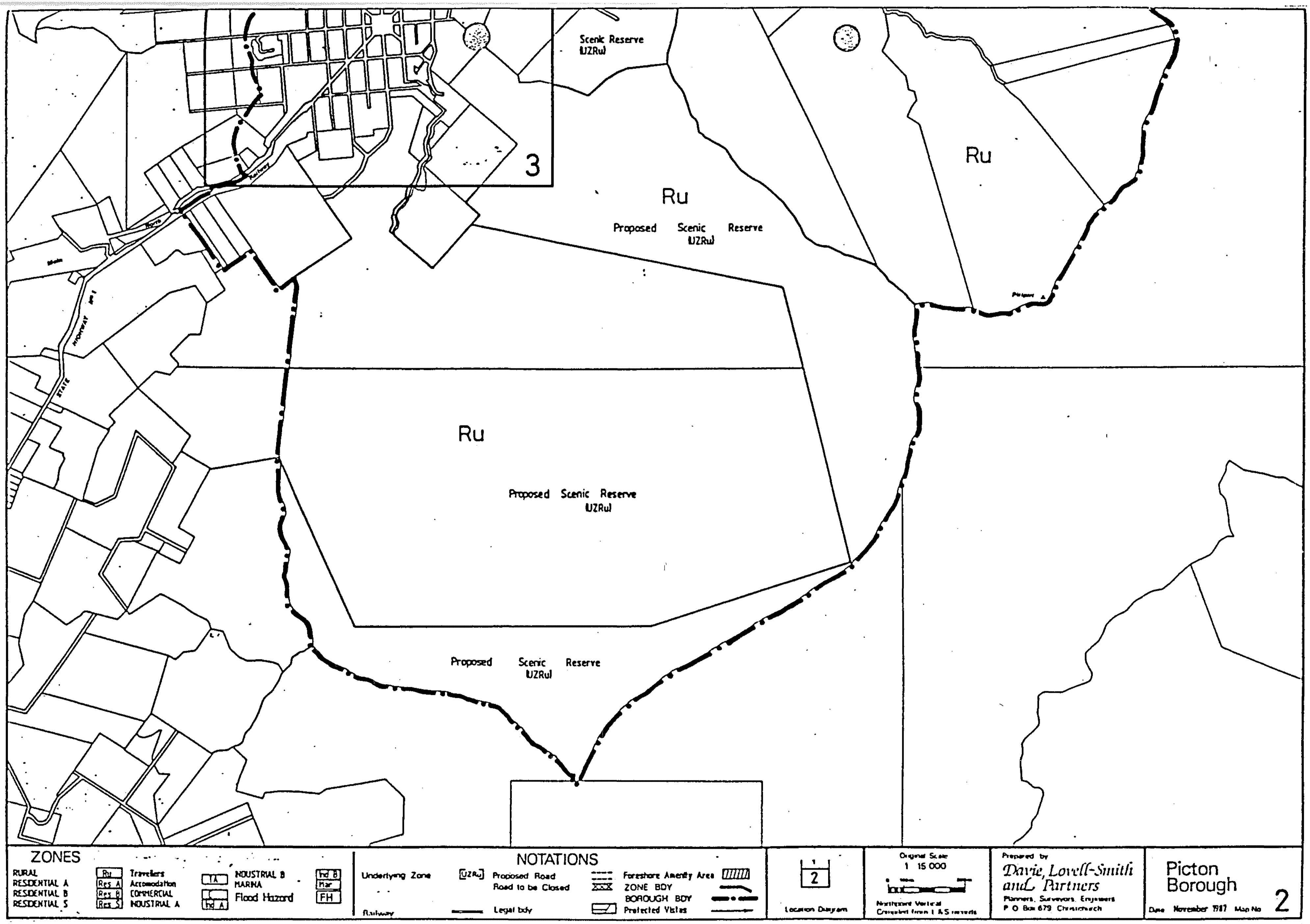
APPENDIX 2.

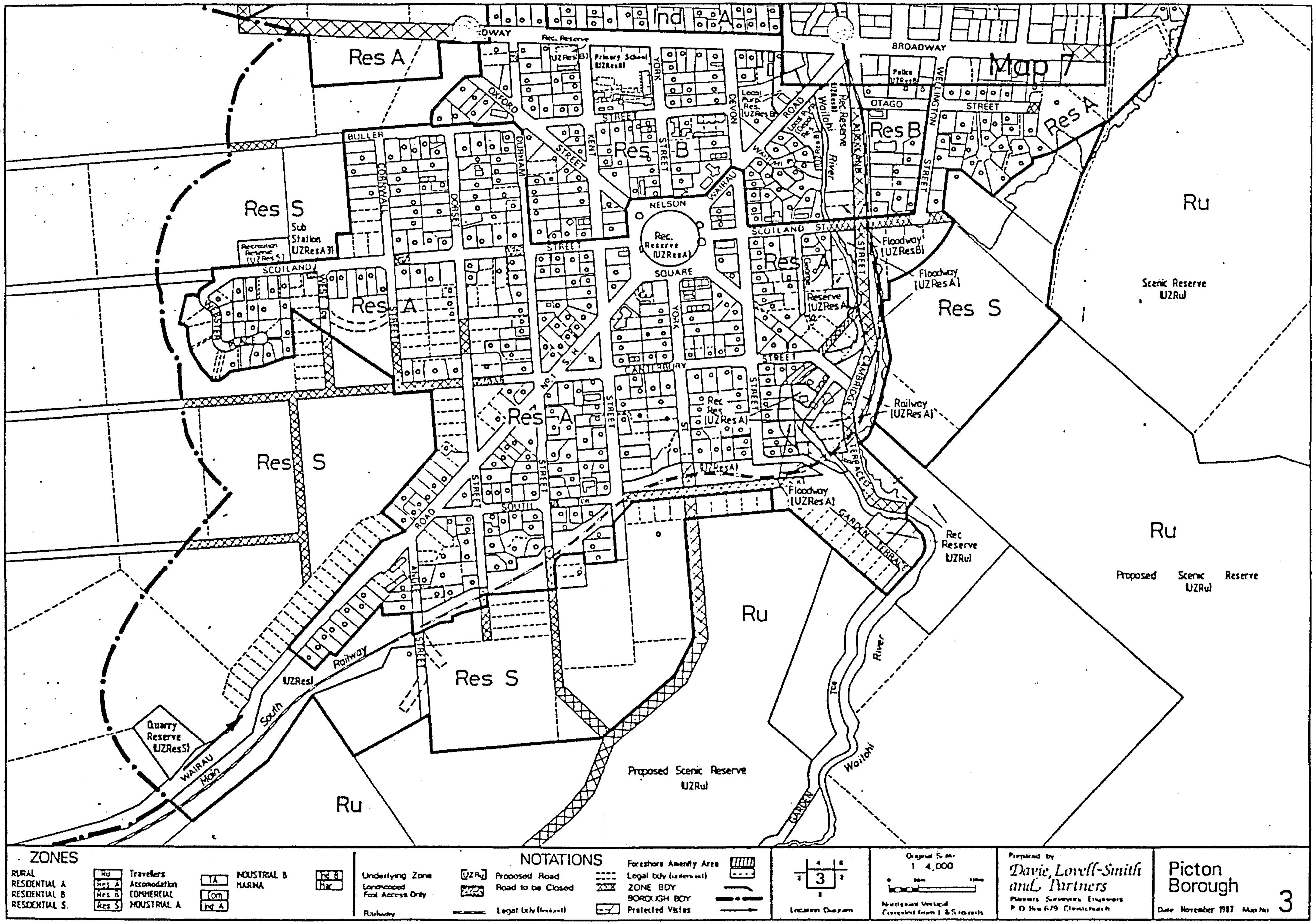
Land use zoning maps for the Picton Borough. Reproduced from the Picton District Scheme Pre-Review Statement, 1988, and due for implementation mid 1989.

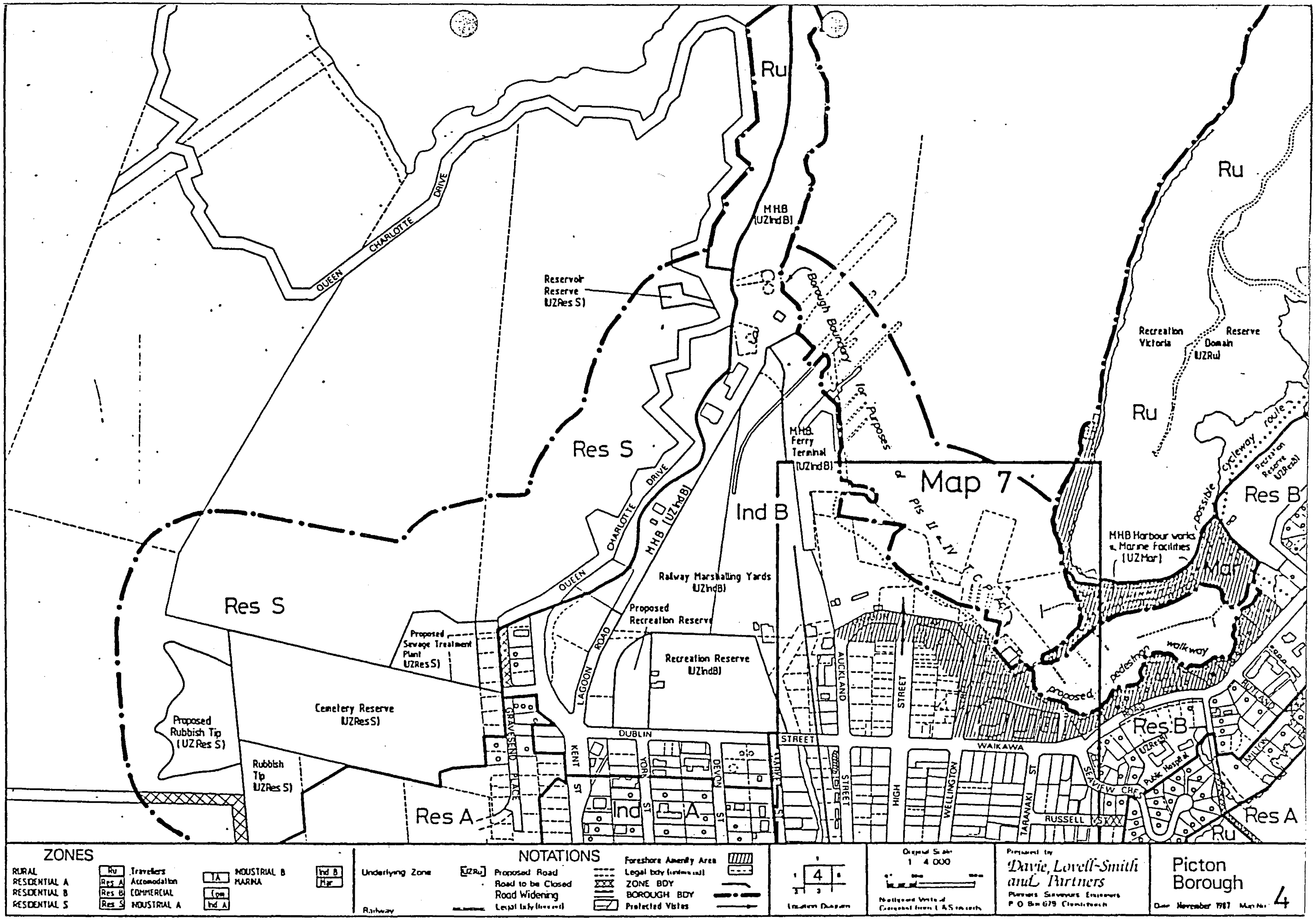


Picton Borough District Planning Scheme
Planning Map Index
Original scale 1:30,000
Northpoint vertical
0
500m
1
2
3
4
5
6
Queen
Charlotte
Sound
Waikawa Bay
Port Underwood Road
Picton
Harbour
Shakespeare Bay
Queen Charlotte Drive
Piripiri
S. H. No. 1


Ru
Res S
Sounds Foreshore Reserve (UZ Res S)
Recreation Reserve (UZRu)
Recreation Reserve (UZRes S)
Proposed Recreation Reserve (UZRu)
Waterworks Area (UZRu)
6
5
4
ZONES
RURAL Ru
RESIDENTIAL A Res A
RESIDENTIAL B Res B
RESIDENTIAL S Res S
Travellers Accomodation TA
COMMERCIAL Com
INDUSTRIAL A Ind A
INDUSTRIAL Ind B
MARINA Mar
Flood Hazard FH
NOTATIONS
Underlying Zone UZRu
Proposed Road
Road to be Closed
Legal bdy
Foreshore Amenity Area
ZONE BDY
BOROUGH BDY
Protected Vistas
1
Original Scale
1 15,000
Prepared by
Davie, Lovell-Smith and Partners
Picton Borough
November 1987
1


Scenic Reserve
(UZRu)
3
Ru
Ru
Proposed Scenic Reserve
(UZRu)
Ru
Proposed Scenic Reserve
(UZRu)
Proposed Scenic Reserve
(UZRu)
Railway
State Highway No 1
ZONES
RURAL Ru
RESIDENTIAL A Res A
RESIDENTIAL B Res B
RESIDENTIAL S Res S
Travellers Accomodation TA
COMMERCIAL
INDUSTRIAL A Ind A
INDUSTRIAL B Ind B
MARINA Mar
Flood Hazard FH
NOTATIONS
Underlying Zone [UZRu]
Railway
Proposed Road
Road to be Closed
Legal bdy
Foreshore Amenity Area
ZONE BDY
BOROUGH BDY
Protected Vistas
Location Diagram
Original Scale
1 15 000
Northpoint Vertical
Compiled from L & S records
Prepared by
Davie, Lovell-Smith and Partners
Planners, Surveyors, Engineers
P O Box 679 Christchurch
Picton Borough
Date November 1987 Map No 2


Res A
Res S
Res B
Ru
Ind A
Map 7
BROADWAY
OTAGO STREET
WELLINGTON STREET
BULLER
OXFORD STREET
KENT
YORK STREET
DEVON
DURHAM STREET
DORSET
CORNWALL
NELSON SQUARE
SCOTLAND STREET
SCOTLAND ST
CANTERBURY STREET
SOUTH
WAIRAU ROAD
CAMBRIDGE
GARDEN TERRACE
S.H. No 1
Primary School (UZResB)
Police (UZResB)
Rec. Reserve (UZResA)
Rec Reserve (UZRes B)
Rec Reserve (UZRu)
Rec Res (UZRes A)
Sub Station (UZResA3)
Recreation Reserve (UZResS)
Floodway (UZResB)
Floodway (UZRes A)
Railway (UZRes A)
Reserve (UZRes A)
Scenic Reserve (UZRu)
Proposed Scenic Reserve (UZRu)
Quarry Reserve (UZResS)
Waitohi River
Main South Railway
ZONES
RURAL Ru
RESIDENTIAL A Res A
RESIDENTIAL B Res B
RESIDENTIAL S. Res S
Travellers Accomodation TA
COMMERCIAL Com
INDUSTRIAL A Ind A
INDUSTRIAL B Ind B
MARINA Mar
NOTATIONS
Underlying Zone
Landscaped Foot Access Only
Railway
Proposed Road
Road to be Closed
Legal bdy
ZONE BDY
BOROUGH BDY
Foreshore Amenity Area
Protected Vistas
Location Diagram
Original Scale 1 : 4,000
Prepared by Davie, Lovell-Smith and Partners
Planners Surveyors Engineers
Picton Borough
Date November 1987 Map No 3


Ru
Ru
Ru
Ru
QUEEN CHARLOTTE DRIVE
QUEEN CHARLOTTE DRIVE
MHB (UZIndB)
MHB (UZ IndB)
Reservoir Reserve (UZRes S)
Borough Boundary for Purposes
Res S
Res S
MHB Ferry Terminal (UZIndB)
Map 7
Ind B
Recreation Victoria Reserve Domain (UZRu)
possible cycleway route
Recreation Reserve (UZResB)
Res B
MHB Harbour works & Marine Facilities (UZMar)
Mar
Railway Marshalling Yards (UZIndB)
Proposed Recreation Reserve
Proposed Sewage Treatment Plant (UZRes S)
Recreation Reserve (UZIndB)
LAGOON ROAD
proposed pedestrian walkway
Cemetery Reserve (UZRes S)
Proposed Rubbish Tip (UZ Res S)
Rubbish Tip (UZRes S)
GRAVESEND PLACE
DUBLIN
KENT ST
YORK ST
DEVON ST
STREET
AUCKLAND STREET
HIGH STREET
WELLINGTON
TARANAKI ST
WAIKAWA
SEAVIEW CRES
RUSSELL ST
Res B
Public Hospital
Res A
Ind A
Res A
Ru
ZONES
RURAL Ru
RESIDENTIAL A Res A
RESIDENTIAL B Res B
RESIDENTIAL S Res S
Travellers Accomodation TA
COMMERCIAL Com
INDUSTRIAL A Ind A
INDUSTRIAL B Ind B
MARINA Mar
NOTATIONS
Underlying Zone UZRu
Railway
Proposed Road
Road to be Closed
Road Widening
Legal bdy (fenced)
Foreshore Amenity Area
Legal bdy (unfenced)
ZONE BDY
BOROUGH BDY
Protected Vistas
4
Location Diagram
Original Scale 1 : 4 000
Prepared by Davie, Lovell-Smith and Partners
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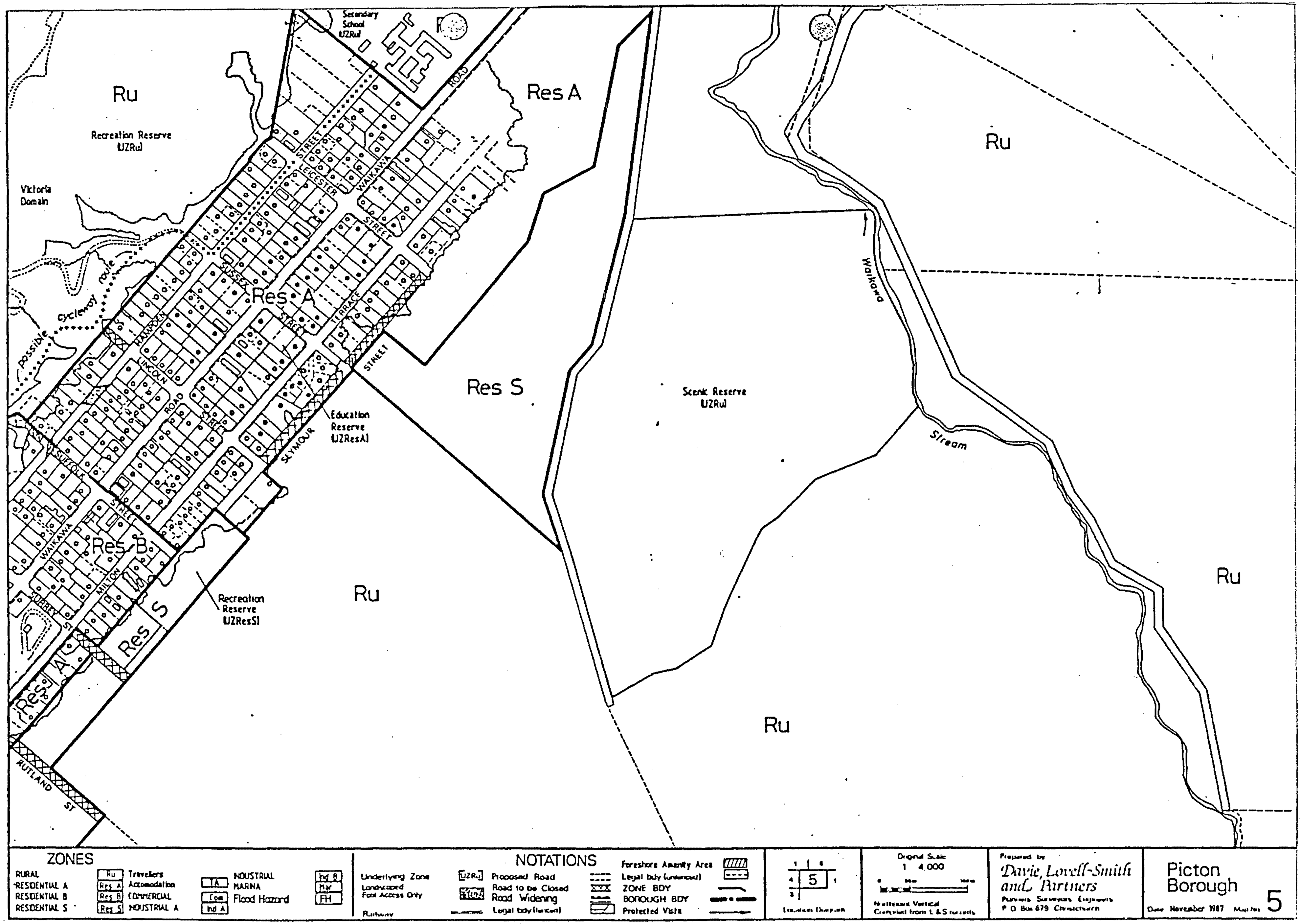
Picton Borough
Date November 1987 Map No. 4



Secondary School UZRu
Ru
Recreation Reserve UZRu
Victoria Domain
Res A
ROAD
STREET
LEICESTER
WAIKAWA
STREET
SUSSEX
Res A
HAMPDEN
STREET
TERRACE
STREET
LINCOLN
ROAD
STREET
possible cycleway route
Res S
Education Reserve UZResA
SEYMOUR
SUFFOLK
STREET
WAIKAWA
Res B
MILTON
SURREY
ST
Res S
Recreation Reserve UZResS
Res A
Res
RUTLAND ST
Ru
Ru
Scenic Reserve UZRu
Waikawa Stream
Ru
Ru
ZONES
RURAL Ru
RESIDENTIAL A Res A
RESIDENTIAL B Res B
RESIDENTIAL S Res S
Travellers Accomodation TA
COMMERCIAL Com
INDUSTRIAL A Ind A
INDUSTRIAL Ind B
MARINA Mar
Flood Hazard FH
NOTATIONS
Underlying Zone UZRu
Landscaped Foot Access Only
Railway
Proposed Road
Road to be Closed
Road Widening
Legal bdy (fenced)
Foreshore Amenity Area
Legal bdy (unfenced)
ZONE BDY
BOROUGH BDY
Protected Vista
5
Location Diagram
Original Scale
1 4,000
Nullhsune Vertical
Compiled from L & S records
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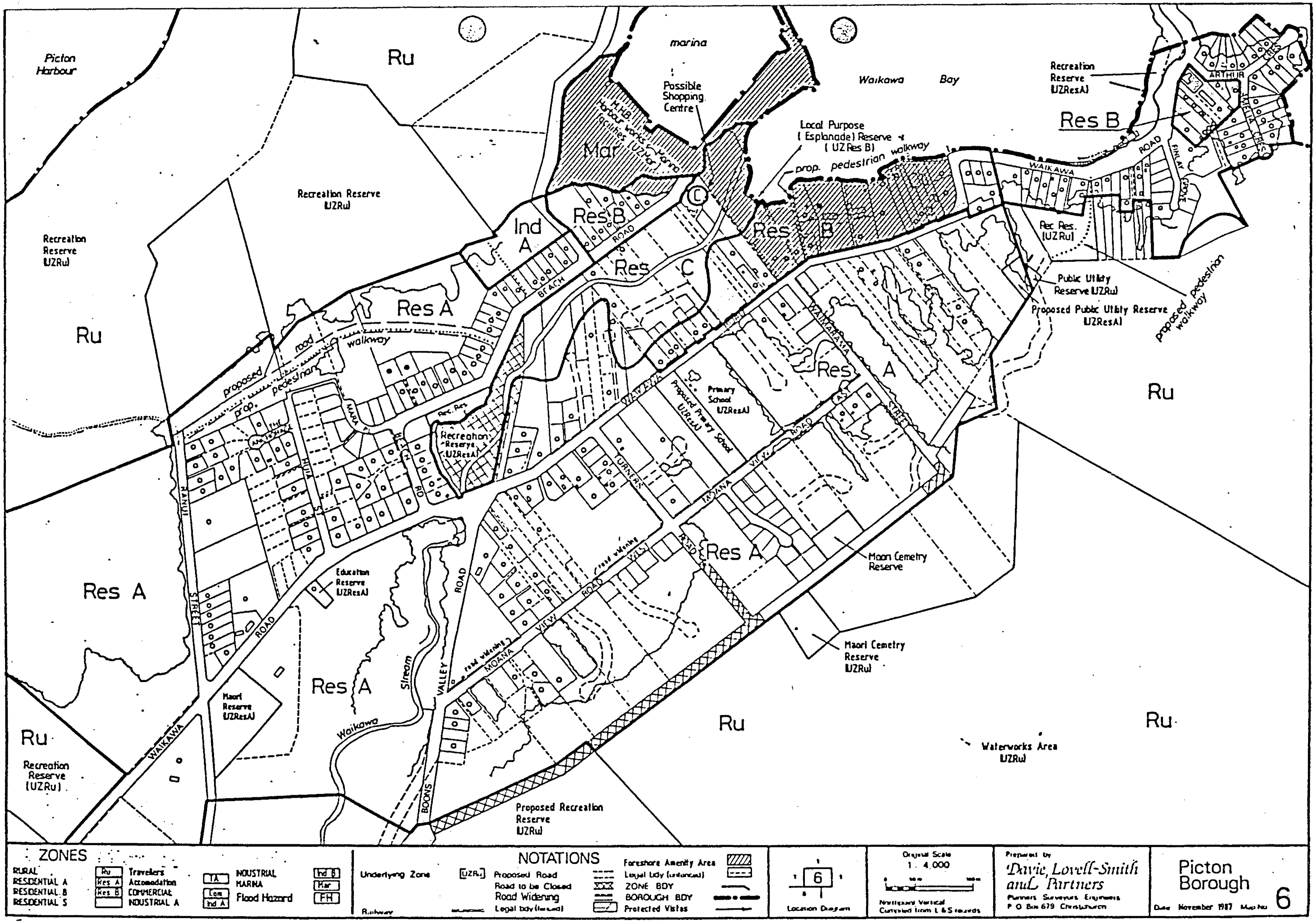
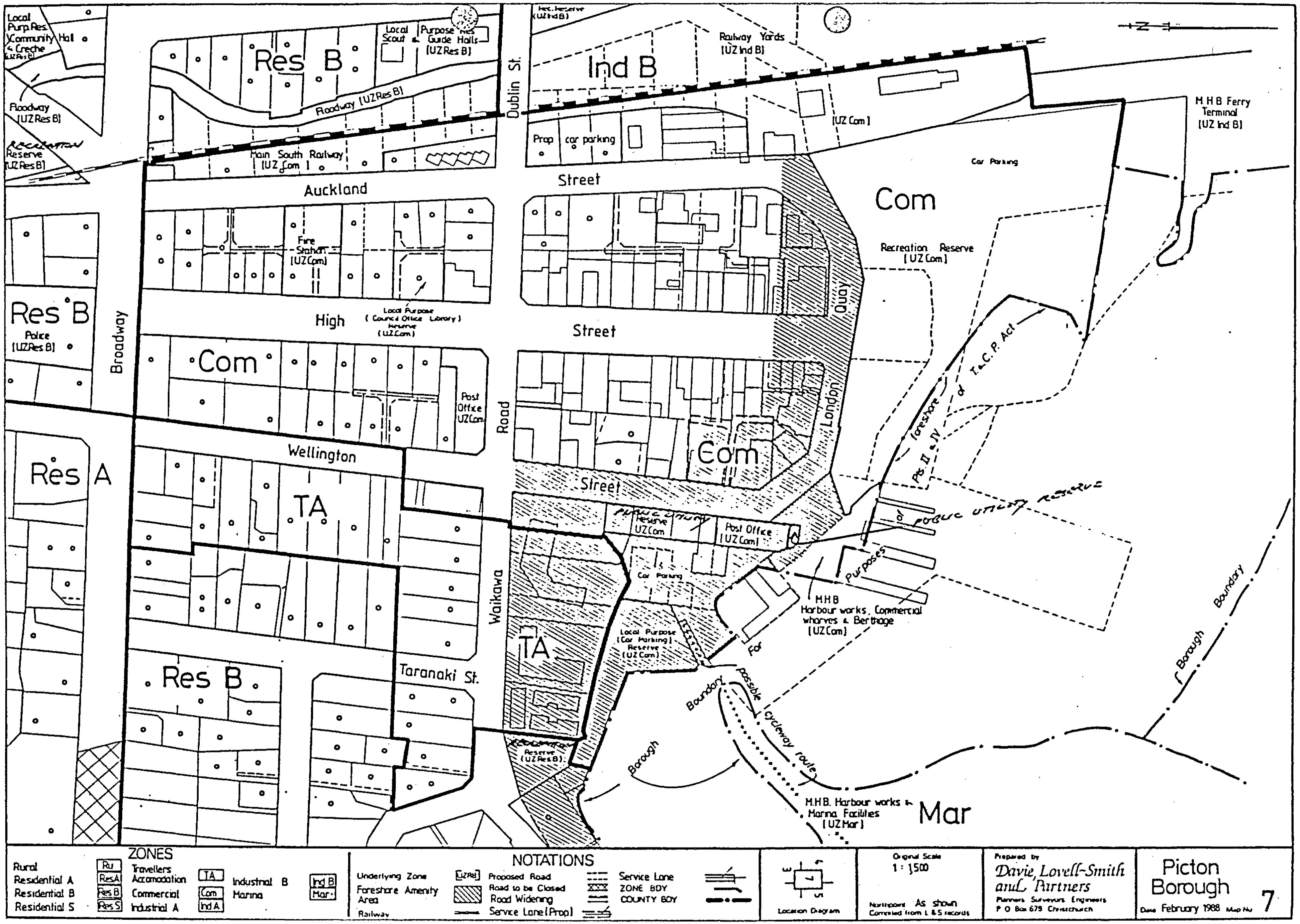
Map No 5

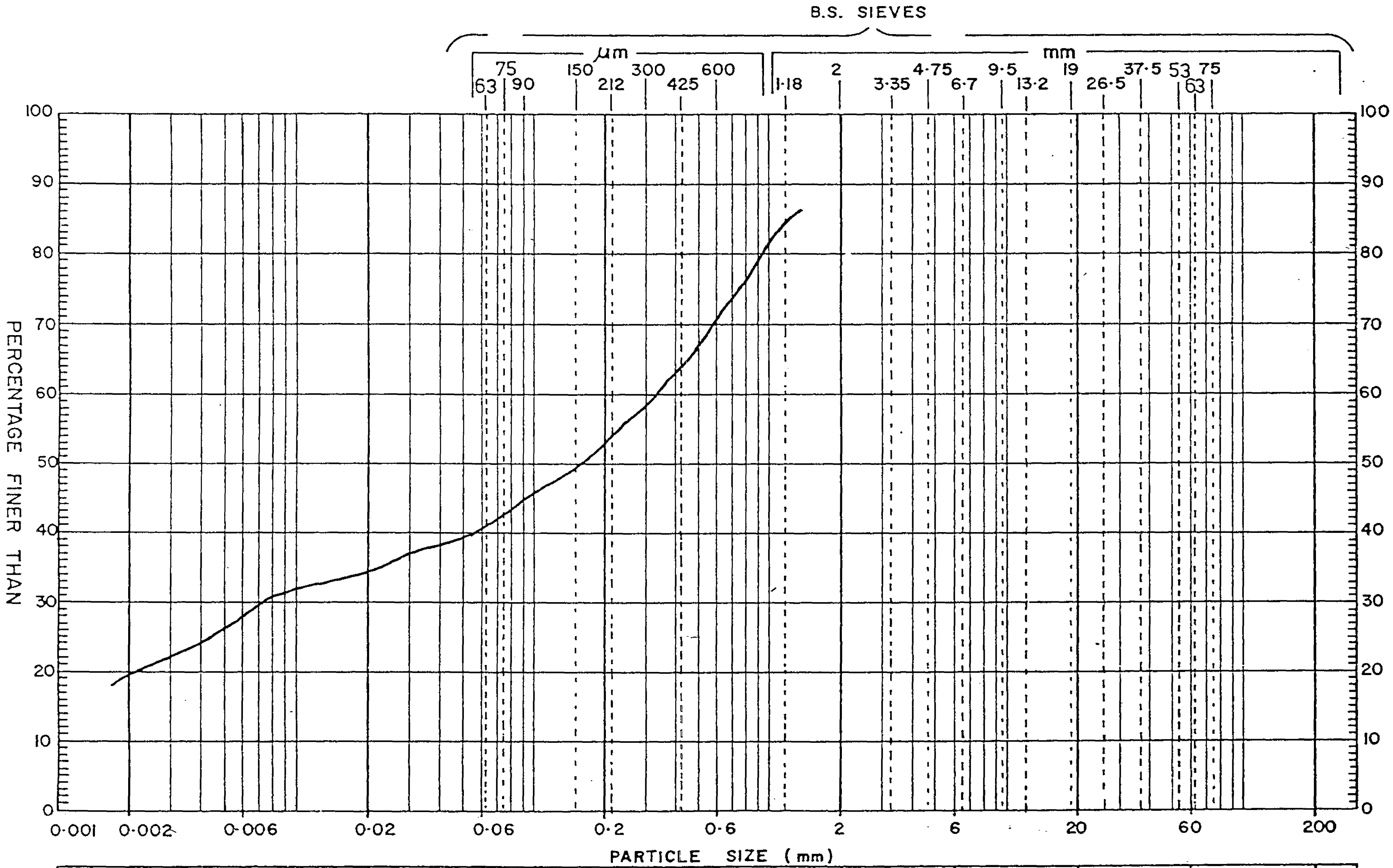


Picton Harbour
Ru
marina
Waikawa Bay
Possible Shopping Centre
M.H.B. Harbour works, marina facilities (UZMar)
Mar
Recreation Reserve (UZResA)
Res B
Local Purpose (Esplanade) Reserve (UZ Res B)
prop. pedestrian walkway
Recreation Reserve (UZRu)
Ind A
Res B
Res C
Res A
proposed road
prop. pedestrian walkway
Rec. Res. (UZ Ru)
Public Utility Reserve (UZRu)
Proposed Public Utility Reserve (UZResA)
proposed pedestrian walkway
Primary School (UZResA)
Proposed Primary School (UZResA)
Recreation Reserve (UZResA)
Education Reserve (UZResA)
Maori Cemetery Reserve
Maori Cemetery Reserve (UZRu)
Maori Reserve (UZResA)
Waikawa Stream
Recreation Reserve (UZRu)
Proposed Recreation Reserve (UZRu)
Waterworks Area (UZRu)
WAIKAWA ROAD
BEACH ROAD
MOANA VIEW ROAD
VALLEY ROAD
BOONS
KANUI STREET
TURNERS
ARTHUR
FINLAY GROVE
WAIKARAMA
road widening
ZONES
RURAL Ru
RESIDENTIAL A Res A
RESIDENTIAL B Res B
RESIDENTIAL S
Travellers Accomodation TA
COMMERCIAL Com
INDUSTRIAL A Ind A
INDUSTRIAL Ind B
MARINA Mar
Flood Hazard FH
NOTATIONS
Underlying Zone UZRu
Proposed Road
Road to be Closed
Road Widening
Legal bdy
Railway
Foreshore Amenity Area
ZONE BDY
BOROUGH BDY
Protected Vistas
Location Diagram
Original Scale 1 : 4,000
Prepared by Davie, Lovell-Smith and Partners
Picton Borough
Date November 1987 Map No 6


Local Purp.Res. Community Hall & Creche [UZ Res B]
Roadway [UZ Res B]
Recreation Reserve [UZ Res B]
Res B
Local Scout & Guide Halls
Purpose Res
[UZ Res B]
Roadway [UZ Res B]
Main South Railway [UZ Com]
Dublin St.
Rec. Reserve (UZ Ind B)
Railway Yards [UZ Ind B]
Ind B
Prop car parking
[UZ Com]
M.H.B Ferry Terminal [UZ Ind B]
Car Parking
Auckland
Street
Com
Fire Station [UZ Com]
Recreation Reserve [UZ Com]
Res B
Police [UZ Res B]
Broadway
High
Local Purpose (Council Office Library) Reserve (UZ Com)
Street
Quay
Com
Post Office UZ Com
Road
London
Foreshore Amenity Pts. II & IV of T.&C.P. Act
Res A
Wellington
Com
TA
Street
Public Utility Reserve UZ Com
Post Office [UZ Com]
of Public Utility Reserve
Purposes
Car Parking
M.H.B Harbour works, Commercial wharves & Berthage [UZ Com]
For
Borough Boundary
Waikawa
TA
Local Purpose (Car Parking) Reserve (UZ Com)
Res B
Taranaki St.
Boundary
possible cycleway route
Borough
Reserve (UZ Res B)
M.H.B. Harbour works & Marina Facilities [UZ Mar]
Mar
ZONES
Rural
Residential A
Residential B
Residential S
Ru
ResA
Res B
Res S
Travellers Accomodation
Commercial
Industrial A
TA
Com
Ind A
Industrial B
Marina
Ind B
Mar
NOTATIONS
Underlying Zone
Foreshore Amenity Area
Railway
[UZ Res]
Proposed Road
Road to be Closed
Road Widening
Service Lane (Prop)
Service Lane
ZONE BDY
COUNTY BDY
Location Diagram
Original Scale 1 : 1500
Northpoint As shown
Compiled from L & S records
Prepared by
Davie, Lovell-Smith and Partners
Planners Surveyors Engineers
P O Box 679 Christchurch
Picton Borough
Date February 1988
Map No 7

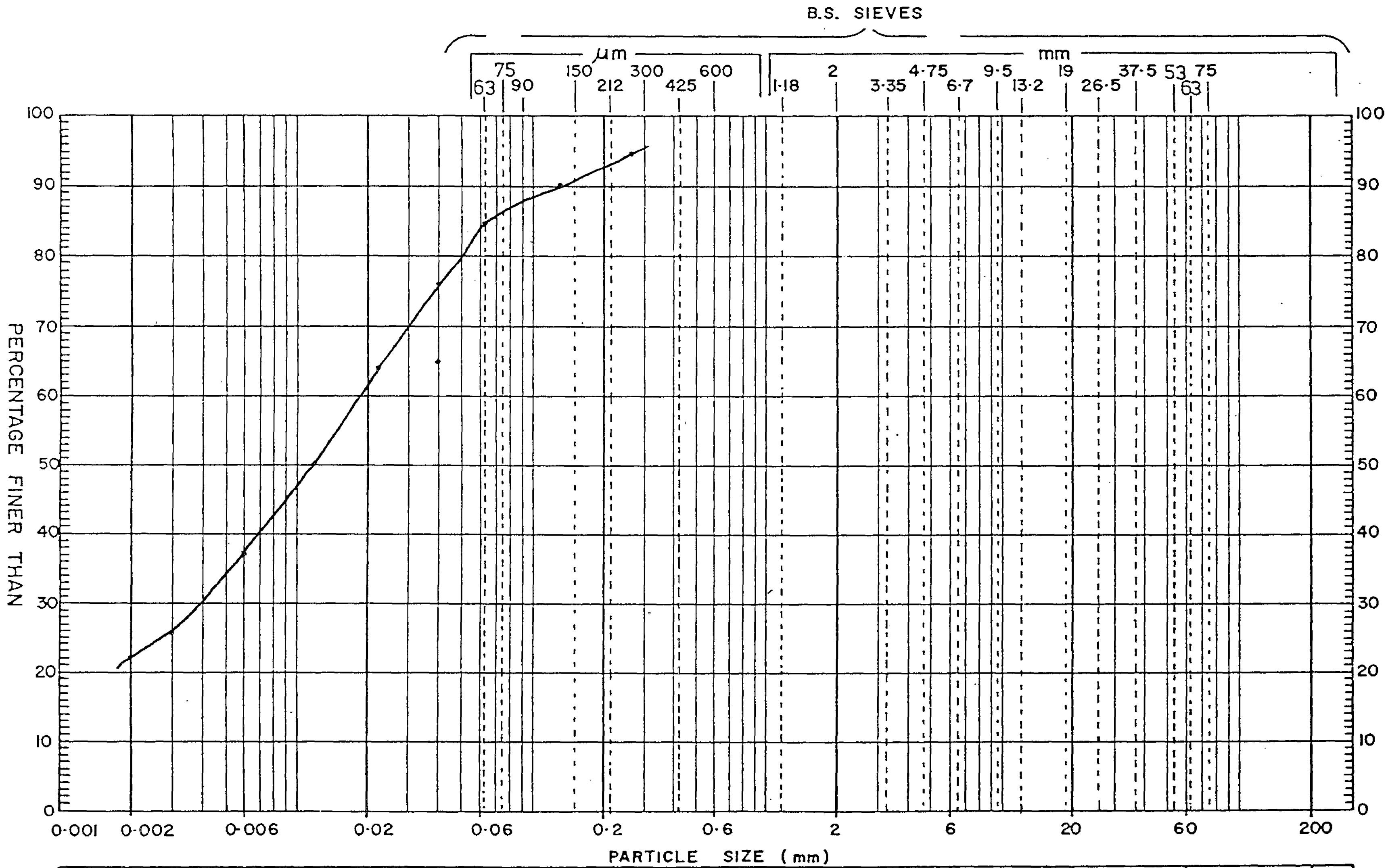
APPENDIX 3

Grainsize distributions for greywacke regolith and colluvium samples.



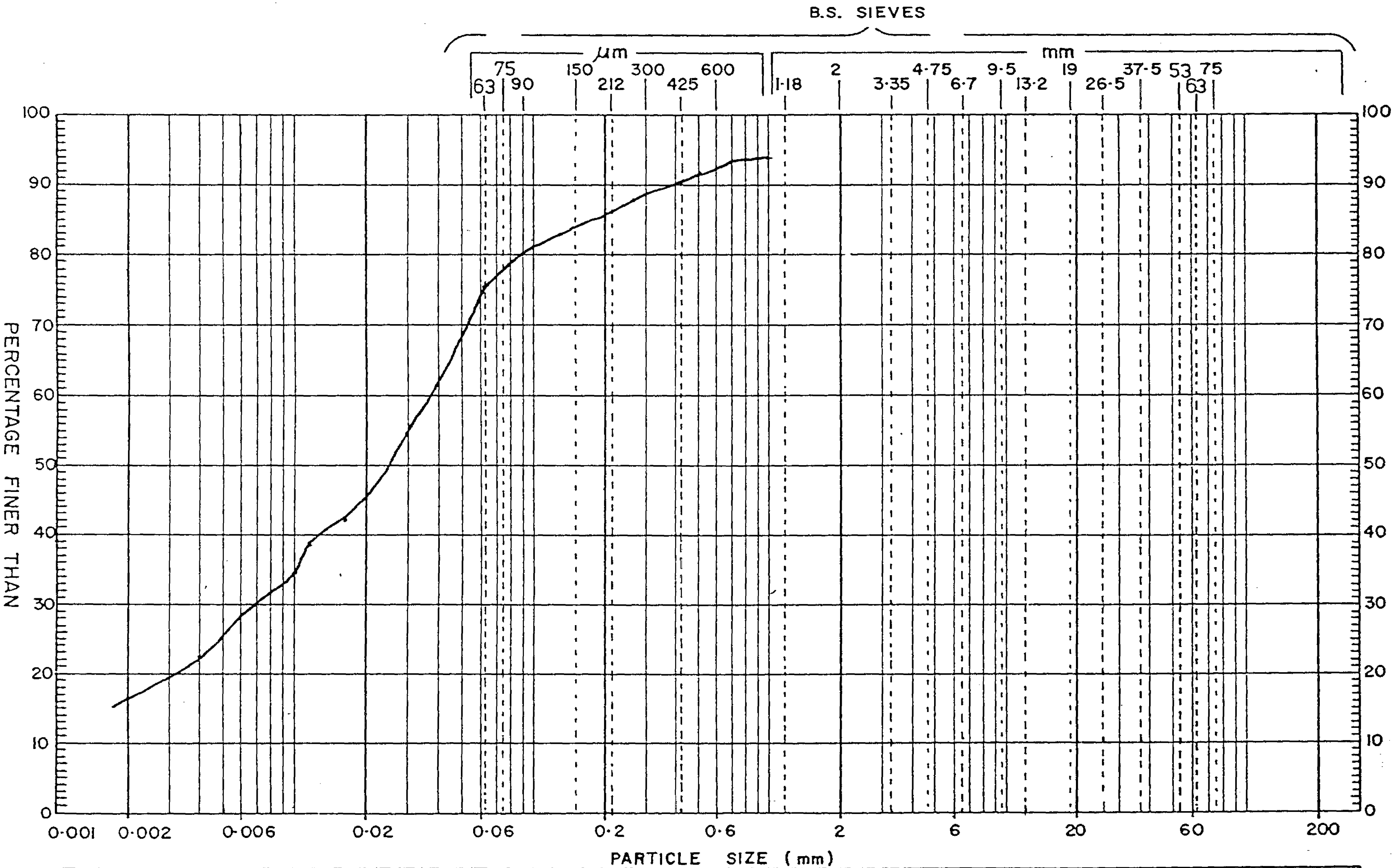
CLAY	FINE	MEDIUM	COARSE	FINE	MEDIUM	COARSE	FINE	MEDIUM	COARSE	V. COARSE	
	SILT			SAND			GRAVEL				

JOB:	SAMPLE No. R1	NATURAL / ~~AIR DRIED / OVEN DRIED / UNKNOWN~~	TESTED BY: P.H.
	LOCATION: BV1	WET SIEVED, DRY SIEVED, PIPETTE, HYDROMETER	DATE: 31/8/88
		REMARKS GREYWACKE REGOLITH	CHECKED BY:
	DEPTH: 2·0 m	WEATHERING GRADE VI	DATE:



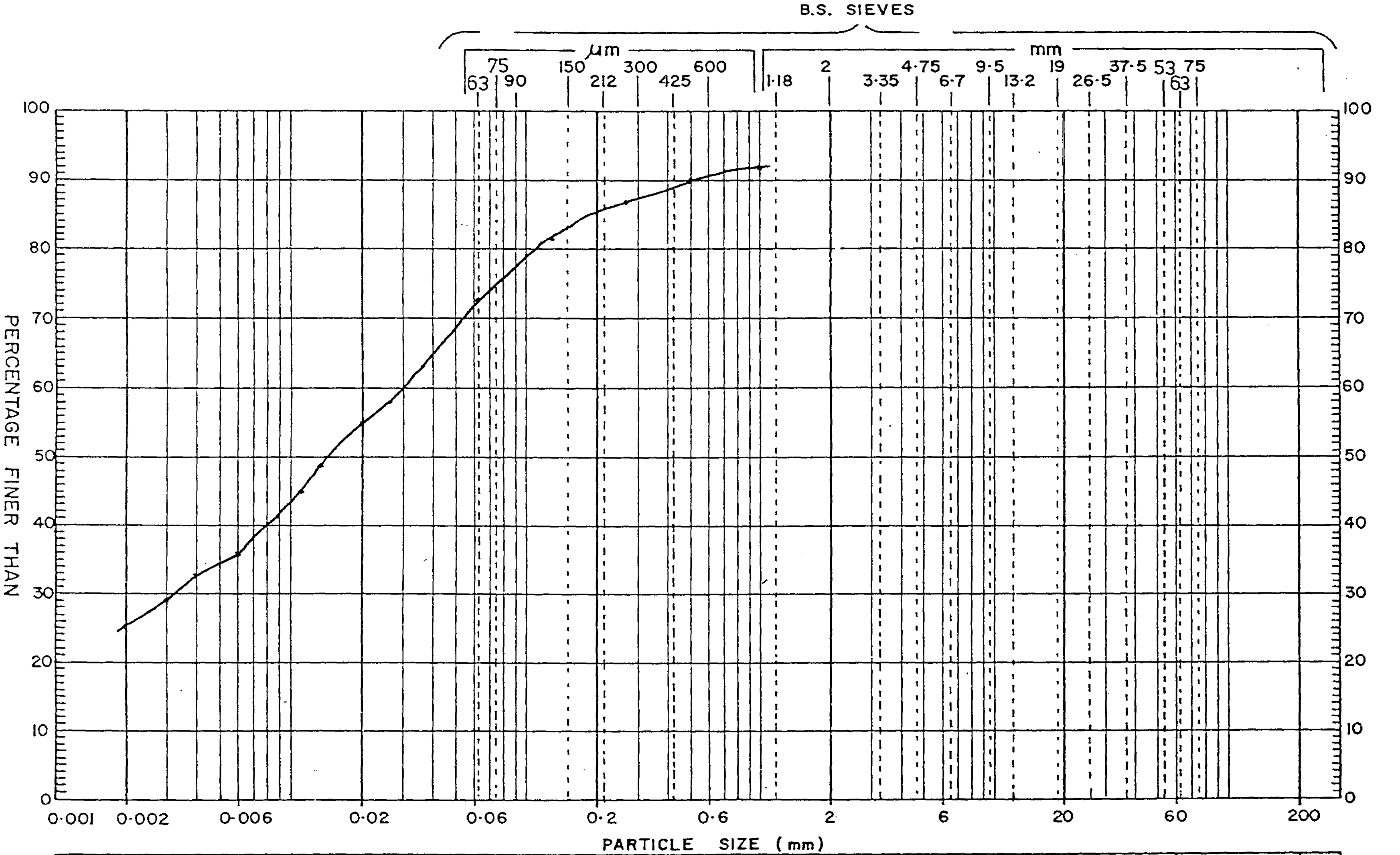
CLAY	FINE	MEDIUM	COARSE	FINE	MEDIUM	COARSE	FINE	MEDIUM	COARSE	V. COARSE	
	SILT			SAND			GRAVEL				

JOB:	SAMPLE No. C6	NATURAL ~~/AIR DRIED/OVEN DRIED/ UNKNOWN~~	TESTED BY: P.H.
	LOCATION: SB1	WET SIEVED, DRY SIEVED, PIPETTE, HYDROMETER	DATE: 30/10/87
		REMARKS SCHIST COLLUVIUM	CHECKED BY:
	DEPTH: 1·5m		DATE:



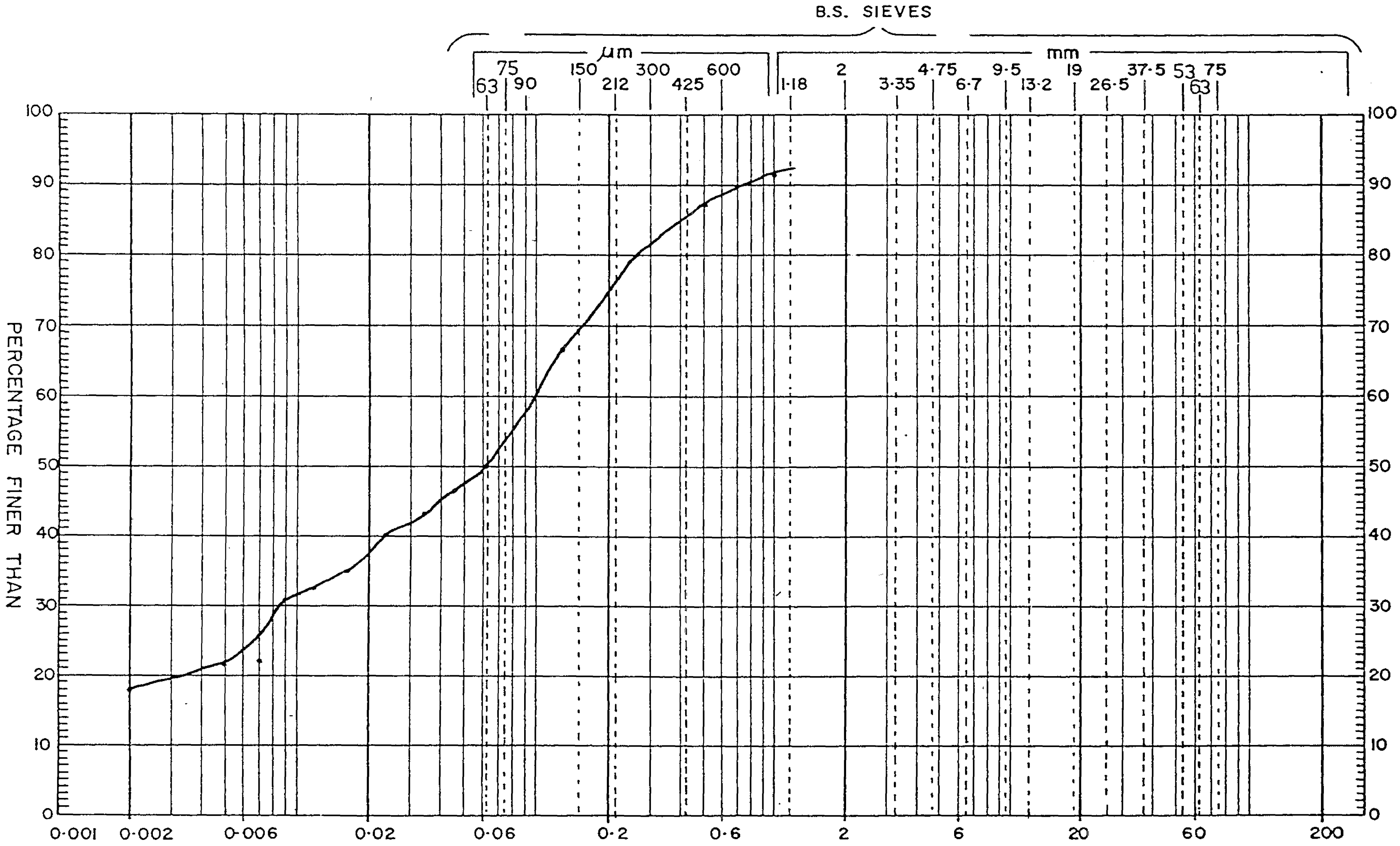
CLAY	FINE	MEDIUM	COARSE	FINE	MEDIUM	COARSE	FINE	MEDIUM	COARSE	V. COARSE
	SILT			SAND			GRAVEL			

JOB:	SAMPLE No. C2	NATURAL / ~~AIR DRIED/OVEN DRIED/ UNKNOWN~~	TESTED BY: P.H.
	LOCATION: JS6	WET SIEVED, DRY SIEVED, PIPETTE, HYDROMETER	DATE: 31/8/88
		REMARKS GREYWACKE COLLUVIUM	CHECKED BY:
	DEPTH: 0·6m		DATE:



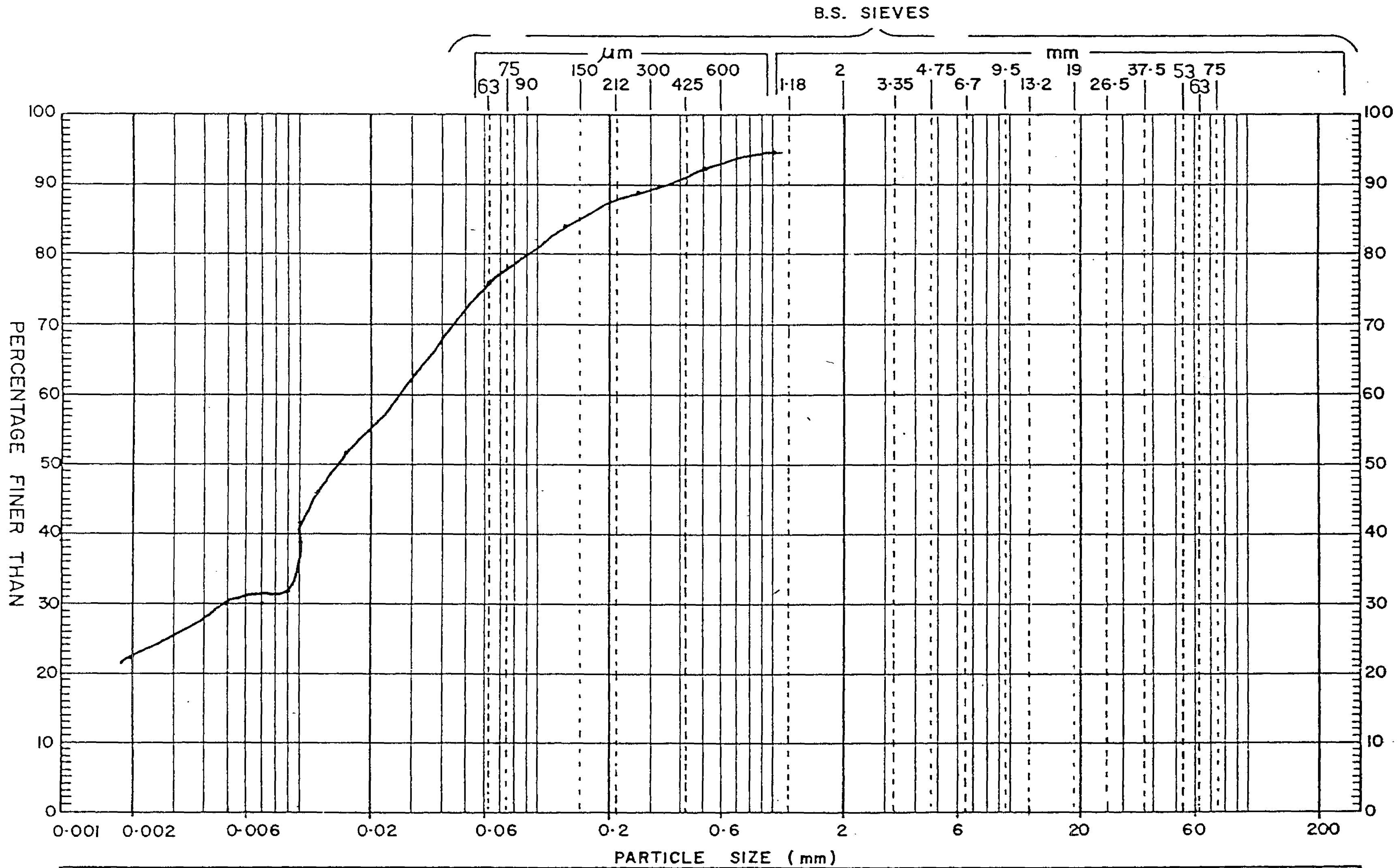
CLAY	FINE	MEDIUM	COARSE	FINE	MEDIUM	COARSE	FINE	MEDIUM	COARSE	V. COARSE	
	SILT			SAND			GRAVEL				

JOB:	SAMPLE No. m2	NATURAL / ~~AIR DRIED/OVEN DRIED/UNKNOWN~~	TESTED BY: P.H.
	LOCATION: WM1	WET SIEVED, DRY SIEVED, PIPETTE, HYDROMETER	DATE: 31/8/88
		REMARKS GREYWACKE COLLUVIUM	CHECKED BY:
	DEPTH: 0·7m		DATE:



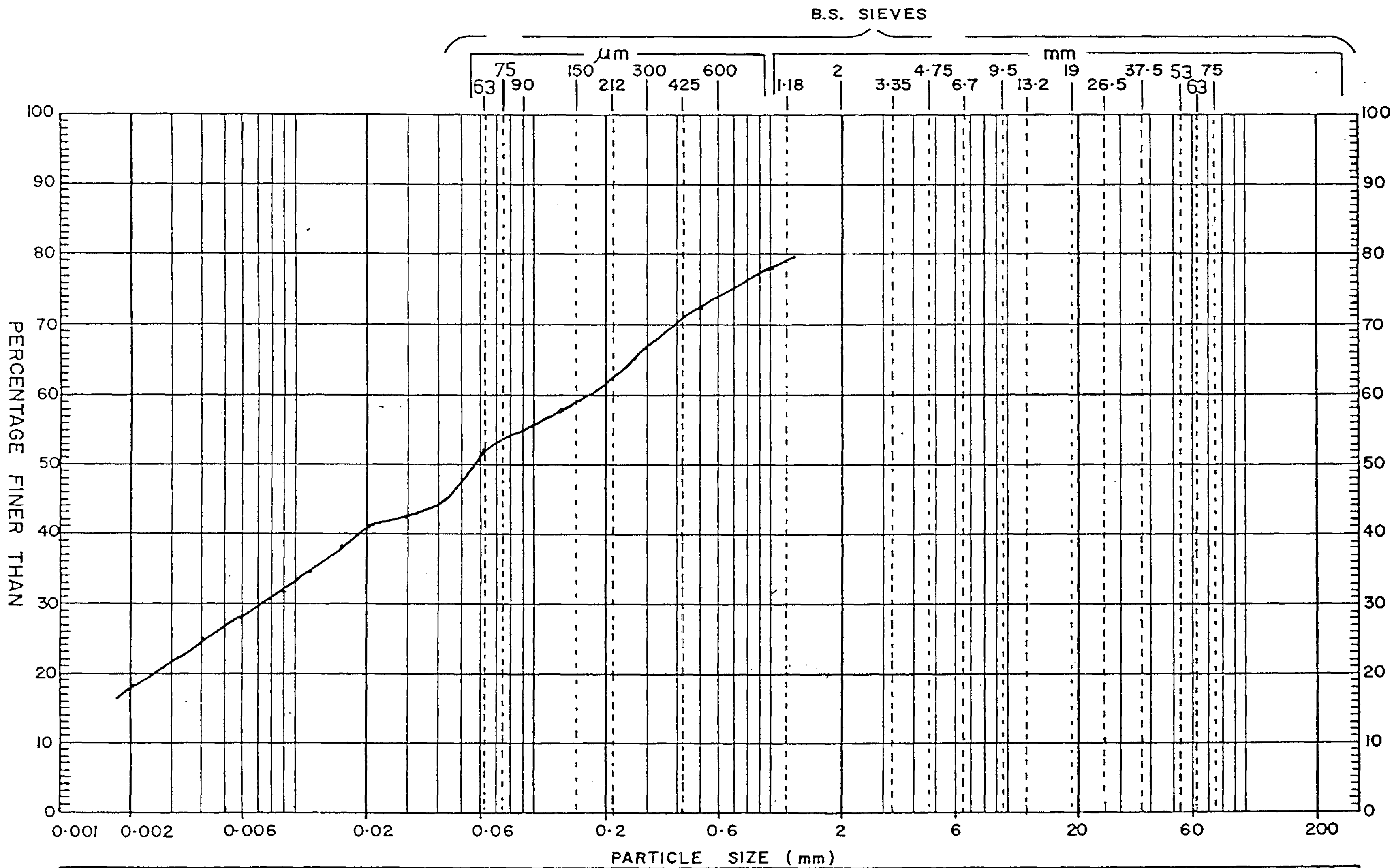
CLAY	FINE	MEDIUM	COARSE	FINE	MEDIUM	COARSE	FINE	MEDIUM	COARSE	V. COARSE	
	SILT			SAND			GRAVEL				

JOB:	SAMPLE No. R5	NATURAL / ~~AIR DRIED / OVEN DRIED / UNKNOWN~~	TESTED BY: P.H
	LOCATION: QC1	WET SIEVED, DRY SIEVED, PIPETTE, HYDROMETER	DATE: 31/8/88
		REMARKS GREYWACKE REGOLITH	CHECKED BY:
	DEPTH: 1·9m	WEATHERING GRADE VI	DATE:



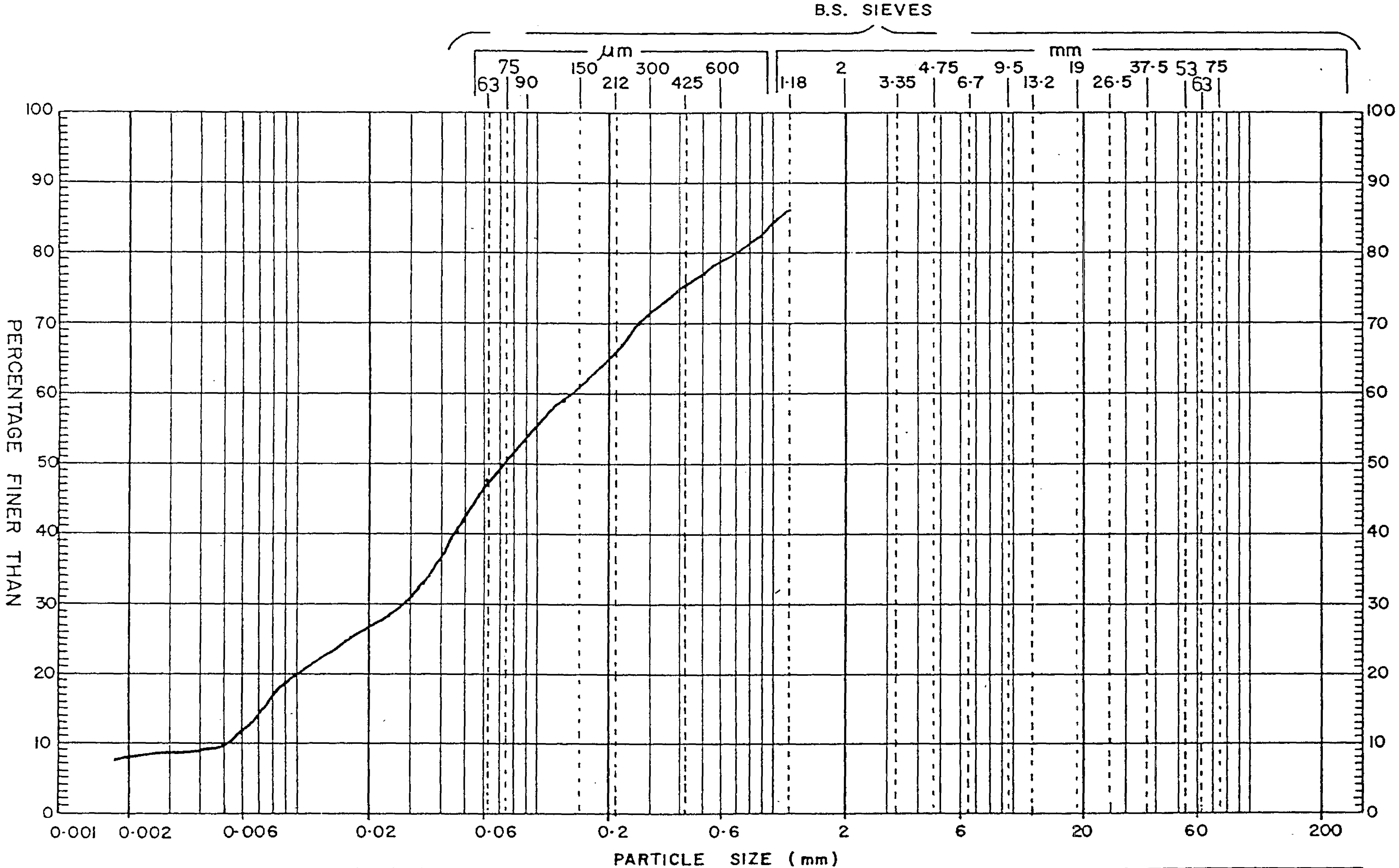
CLAY	FINE	MEDIUM	COARSE	FINE	MEDIUM	COARSE	FINE	MEDIUM	COARSE	V. COARSE	
	SILT			SAND			GRAVEL				

JOB:	SAMPLE No. C5	NATURAL / ~~AIR DRIED/OVEN DRIED/ UNKNOWN~~	TESTED BY: P. H.
	LOCATION: PR1	WET SIEVED, DRY SIEVED, PIPETTE, HYDROMETER	DATE: 31/8/88
		REMARKS GREYWACKE COLLUVIUM	CHECKED BY:
	DEPTH: 1·85 m		DATE:



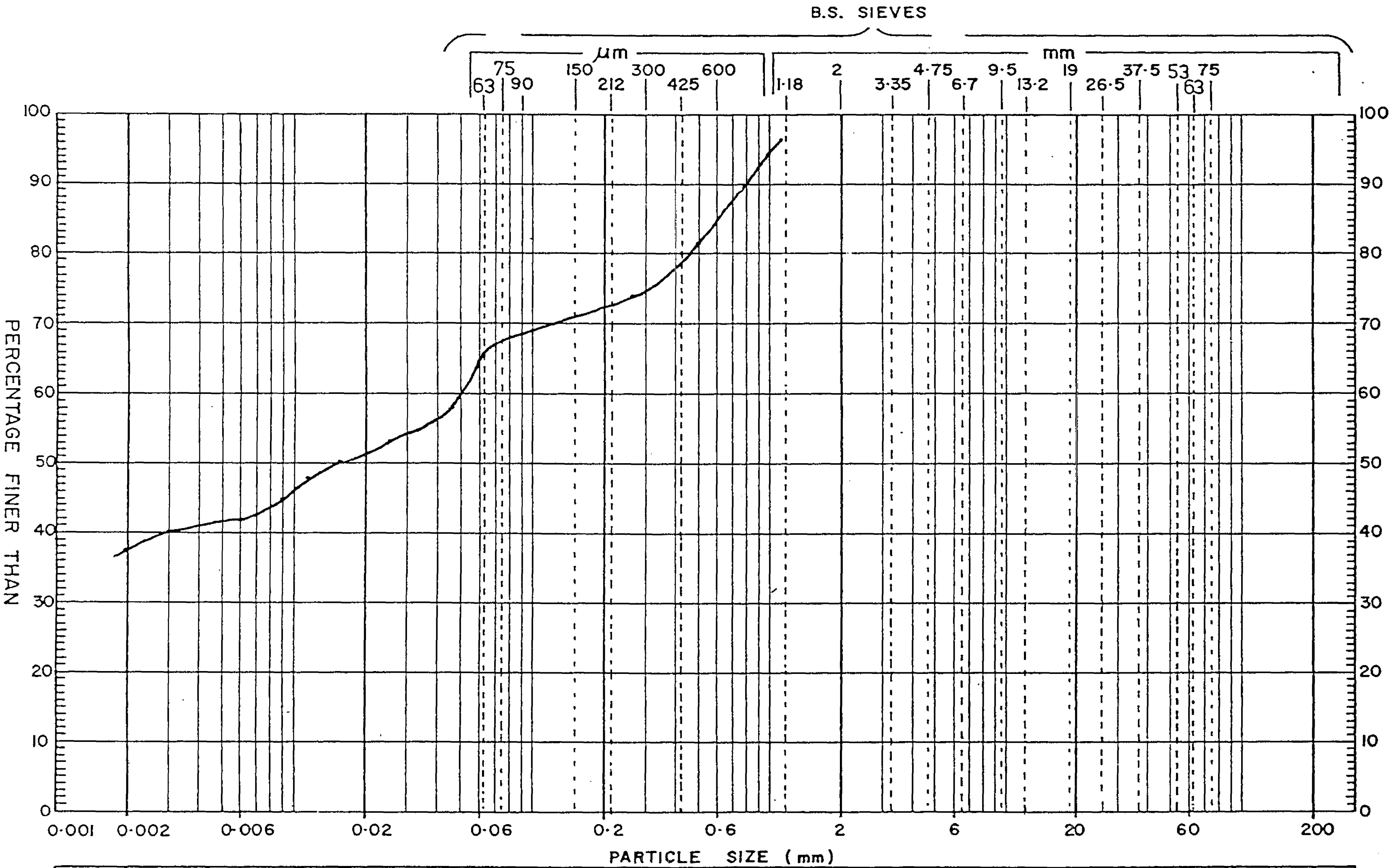
CLAY	FINE	MEDIUM	COARSE	FINE	MEDIUM	COARSE	FINE	MEDIUM	COARSE	V. COARSE	
	SILT			SAND			GRAVEL				

JOB:	SAMPLE No. J8	NATURAL / ~~AIR DRIED/OVEN DRIED/UNKNOWN~~	TESTED BY: P.H
	LOCATION: JS4	WET SIEVED, DRY SIEVED, PIPETTE, HYDROMETER	DATE: 31/8/88
		REMARKS GREYWACKE COLLUVIUM	CHECKED BY:
	DEPTH: 0.25m		DATE:



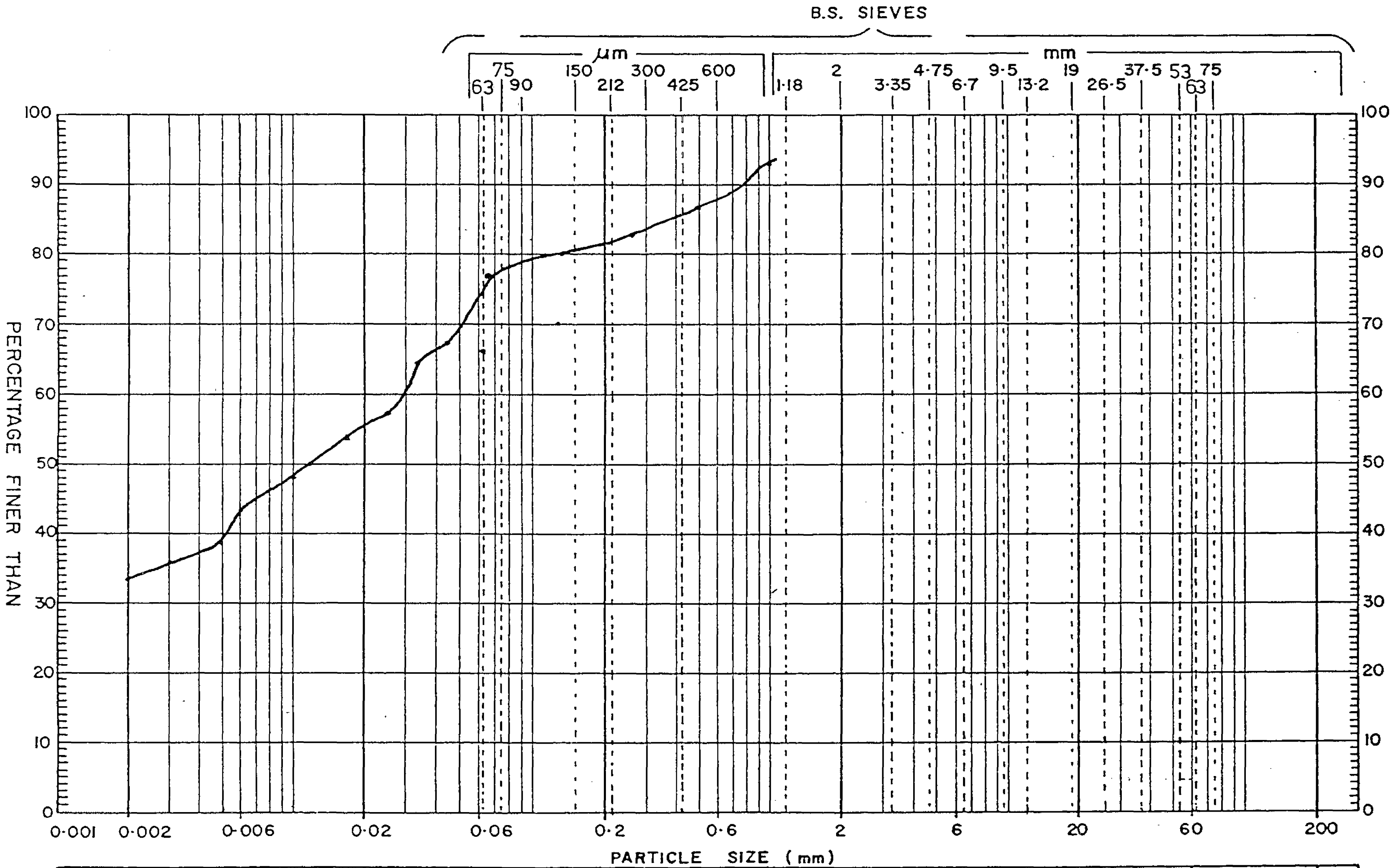
CLAY	FINE	MEDIUM	COARSE	FINE	MEDIUM	COARSE	FINE	MEDIUM	COARSE	V. COARSE
	SILT			SAND			GRAVEL			

JOB:	SAMPLE No. J9	NATURAL/AIR DRIED/OVEN DRIED/ UNKNOWN	TESTED BY: P.H.
	LOCATION: JS 5	WET SIEVED, DRY SIEVED, PIPETTE, HYDROMETER	DATE: 31/8/88
		REMARKS GREY WACKE COLLUVIUM	CHECKED BY:
	DEPTH: 0·5m		DATE:



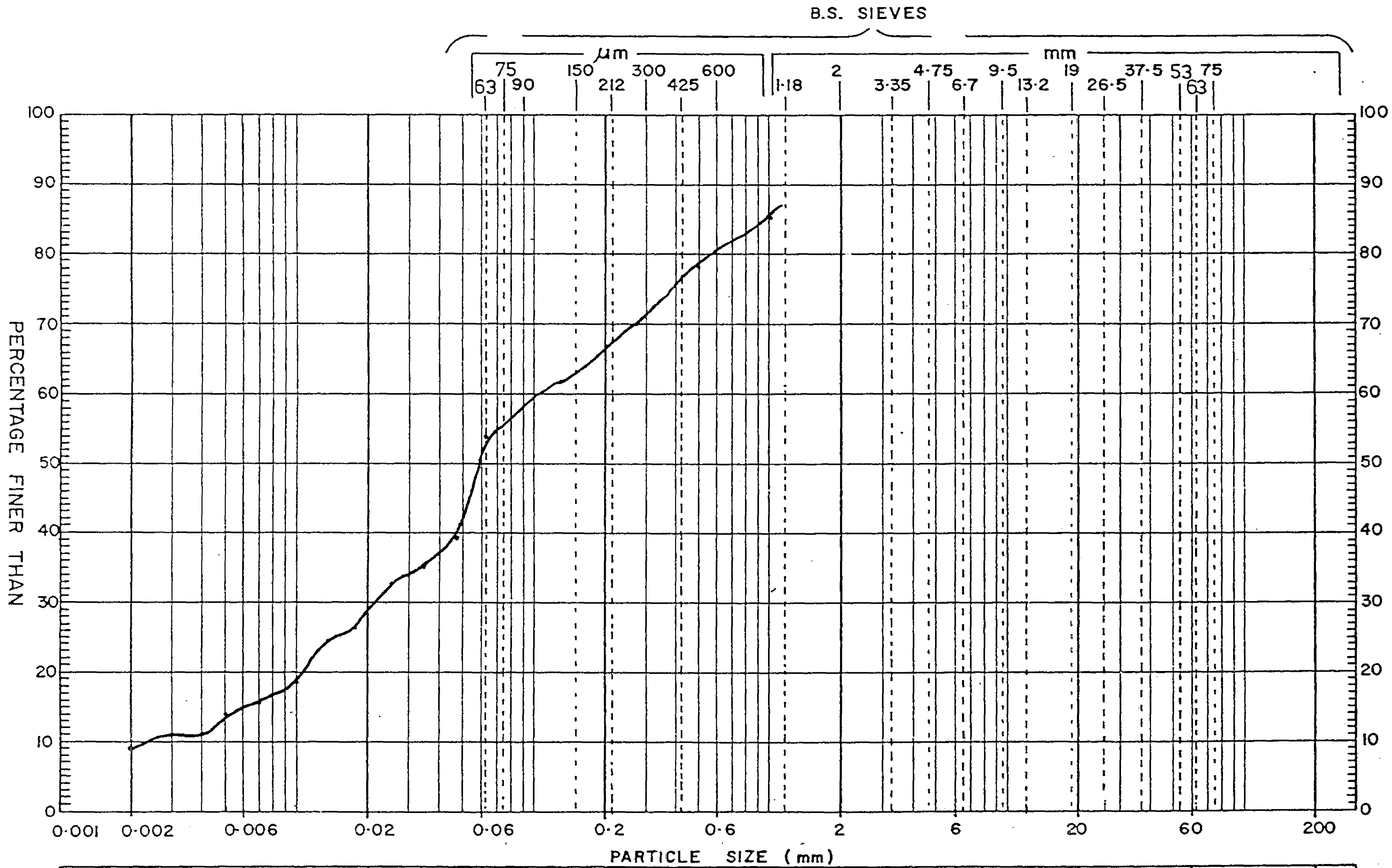
CLAY	FINE	MEDIUM	COARSE	FINE	MEDIUM	COARSE	FINE	MEDIUM	COARSE	V. COARSE
	SILT			SAND			GRAVEL			

JOB:	SAMPLE No. R4	NATURAL / ~~AIR DRIED/OVEN DRIED/UNKNOWN~~	TESTED BY: P.H.
	LOCATION: WR3	WET SIEVED, DRY SIEVED, PIPETTE, HYDROMETER	DATE: 31/8/88
		REMARKS GREYWACKE REGOLITH	CHECKED BY:
	DEPTH: 1·0m	WEATHERING GRD VI	DATE:



CLAY	FINE	MEDIUM	COARSE	FINE	MEDIUM	COARSE	FINE	MEDIUM	COARSE	V. COARSE	
	SILT			SAND			GRAVEL				

JOB:	SAMPLE No. R2	NATURAL/~~AIR DRIED/OVEN DRIED/UNKNOWN~~	TESTED BY: P.H.
	LOCATION: 8V1	WET SIEVED, DRY SIEVED, PIPETTE, HYDROMETER	DATE: 31/8/88
		REMARKS GREYWACKE REGOLITH	CHECKED BY:
	DEPTH: 1·0 m	WTHNG GRD. VI	DATE:



CLAY	FINE	MEDIUM	COARSE	FINE	MEDIUM	COARSE	FINE	MEDIUM	COARSE	V. COARSE	
	SILT			SAND			GRAVEL				

JOB:	SAMPLE No. R3	NATURAL / ~~AIR DRIED/OVEN DRIED/UNKNOWN~~	TESTED BY: P.H
	LOCATION: WR3	WET SIEVED, DRY SIEVED, PIPETTE, HYDROMETER	DATE: 31/8/88
		REMARKS GREYWACKE REGOLITH	CHECKED BY:
	DEPTH: 1·0 m	WEATHERING GRADE V	DATE:

APPENDIX 4

Additional exposure logs.

WR1

Highly weathered mid yellow angular greywacke granules (up to 5 mm), with very occasional slightly weathered Quartz granules in a dry, lose whitish yellow clayey silt matrix

Highly weathered Alluvial Gravels in damp compact yellow silty Clay matrix

Poorly Sorted, slightly weathered alluvial gravels (greywacke) Clasts range from granule size to 150 mm dia. Weakly Imbricated, set in damp silty clay matrix.

(W1 GRAVELS)

WR2

As for WR1

Poorly Sorted damp mid yellow completely weathered sub-rounded Alluvial gravels, in places showing red weathering.
(W0 GRAVELS)

WR3

AS For W1

SAMPLE R4

Completely weathered greywacke bedrock. Mid yellow highly compact damp clay, with occasional granular litho relics.

Completely weathered white quartz veins noted at 2.1 - 2.2 metres

SAMPLE R3

WM1

Angular, poorly sorted greywacke blocks in fine silty Clay matrix.

Slope Colluvium

SAMPLE M2

Sharp lower contact

Highly weathered, highly fractured iron stained Greywacke bedrock.

Gradual transition to:

Moderately weathered, highly fractured greywacke bedrock.

Occasional mudstone horizons.

Deeply iron stained

SAMPLES M1 and M3

P.R. 1

Poorly Sorted Angular bedrock (Greywacke) blocks up to 150 mm dia in damp yellow/brown silty Clay Matrix. Landslide deposits.

SAMPLE C5

QC 1

ORGANIC TOPSOIL

Dry, loose Yellow Clays, with occasional small angular greywacke granules Some fine Silt.

Highly Weathered damp yellow compact clays formed by Complete weathering of greywacke bedrock.

SAMPLE R5

BV1

Dark brown / black highly organic clayey silts.

Deep yellow compact damp Silty clay, occasional small highly weathered greywacke litho relics

SAMPLE R2

Sharp contact

Highly compact brick red damp clay, with some silt. Red weathered throughout.

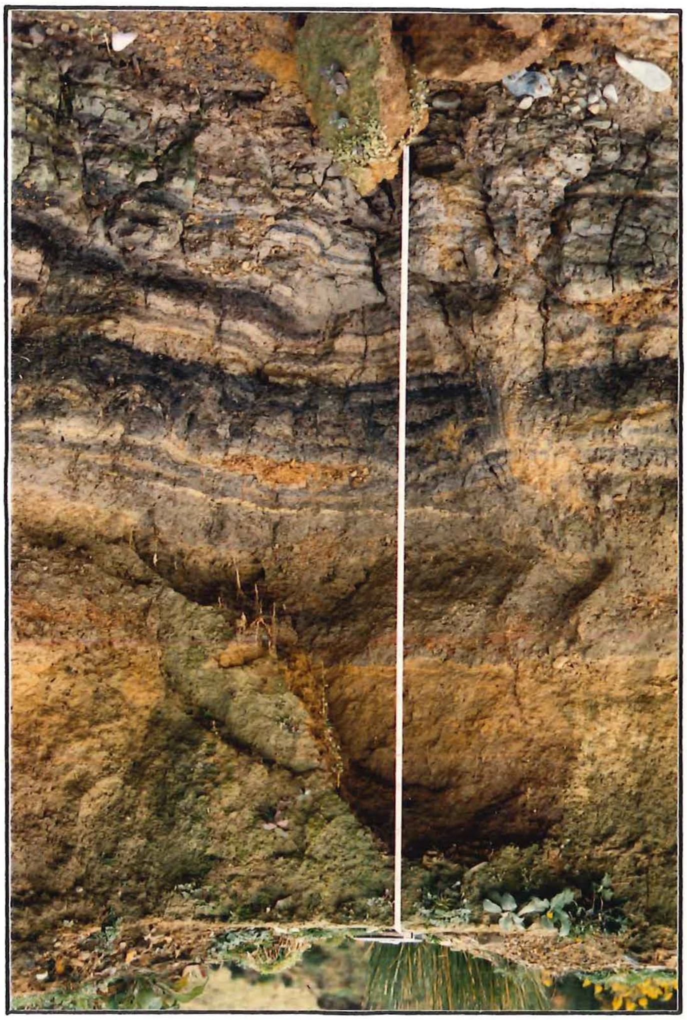
SAMPLE R1

METRES

* SEE FIGURE 3.2 FOR LOCATIONS.

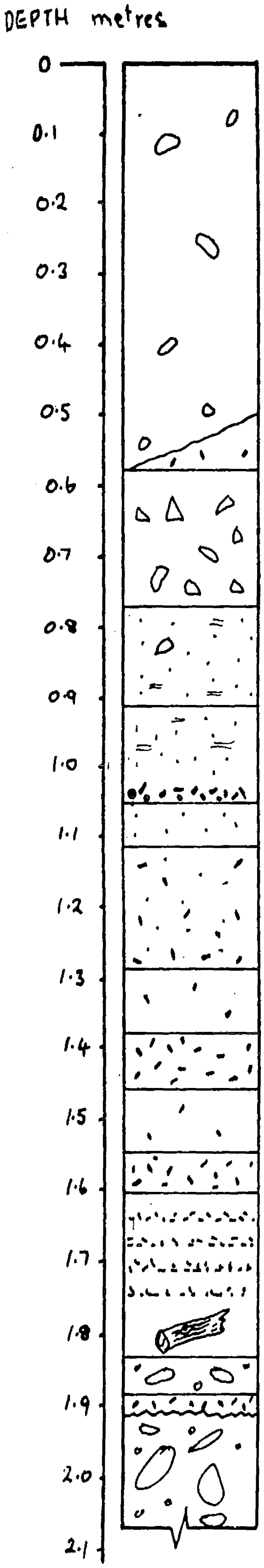
APPENDIX 5

Measured section and sampling details for locality WS1 (see figure 3.2 for location).



Buried swamp deposits at location WS1, Waikawa Stream (see measured section).

MEASURED SECTION
LOCALITY WS1 WAIKAWA STREAM



W_4 SURFACE

DARK GREYISH Brown MOIST SANDY CLAY WITH Some SILT CONTAINING HIGHLY WEATHERED SLIGHTLY SCHISTOSE CLASTS < 25mm Occasional charcoal fragments, MODERN ROOTS TRROUGOUT

MOIST MID YELLOW SILTY CLAY WITH OCC. CHARC FRAGS AND FINER DISSEMINATED CHARCOAL. RARE HIGHLY WEATHERED ANGULAR BEDROCK CLASTS < 20 mm MODERN ROOTS. LENSES OUT LATERALLY

DARK GREY BROWN moist silty WITH SOME SAND. FREQUENT ANG. FRAGMENTS OF HIGHLY WEATHERED BEDROCK < 50 mm

MOIST YELLOW BROWN SILTY SAND. CHARC FRAGS. RARE HIGLY WEATHERED GREYWACKE GRAVEL CLASTS.

MOIST YELLOW SILTY CLAY, CONTAINING CHARCOAL

20 mm thick basal horizon of COARSE CHARCOAL FRAGMENTS

MOIST DARK YELLOW SANDY FINE GRAVEL WITH SOME CLAY

MOIST SILTY CLAY, DARK GREY, CONTAINING COARSE – FINE CHARC. FRAGS.

AS ABOVE, BUT SIGNIFICANTLY LESS CHARCOAL

MOIST DARK GREY SILTY CLAY. ABUNDANT CHARCOAL

AS ABOVE BUT SIGNIFICANTLY LESS CHARCOAL

MOIST DARK GREY SILTY CLAY. ABUNDANT CHARCOAL.

CHARCOAL RICH LAYERS IN MOIST DARK GREY SILTY CLAY

BURIED WOOD (SAMPLED FOR C14 DATING)

POORLY SORTED ROUNDED GREYWACKE GRAVELS in SILTY MATRIX.

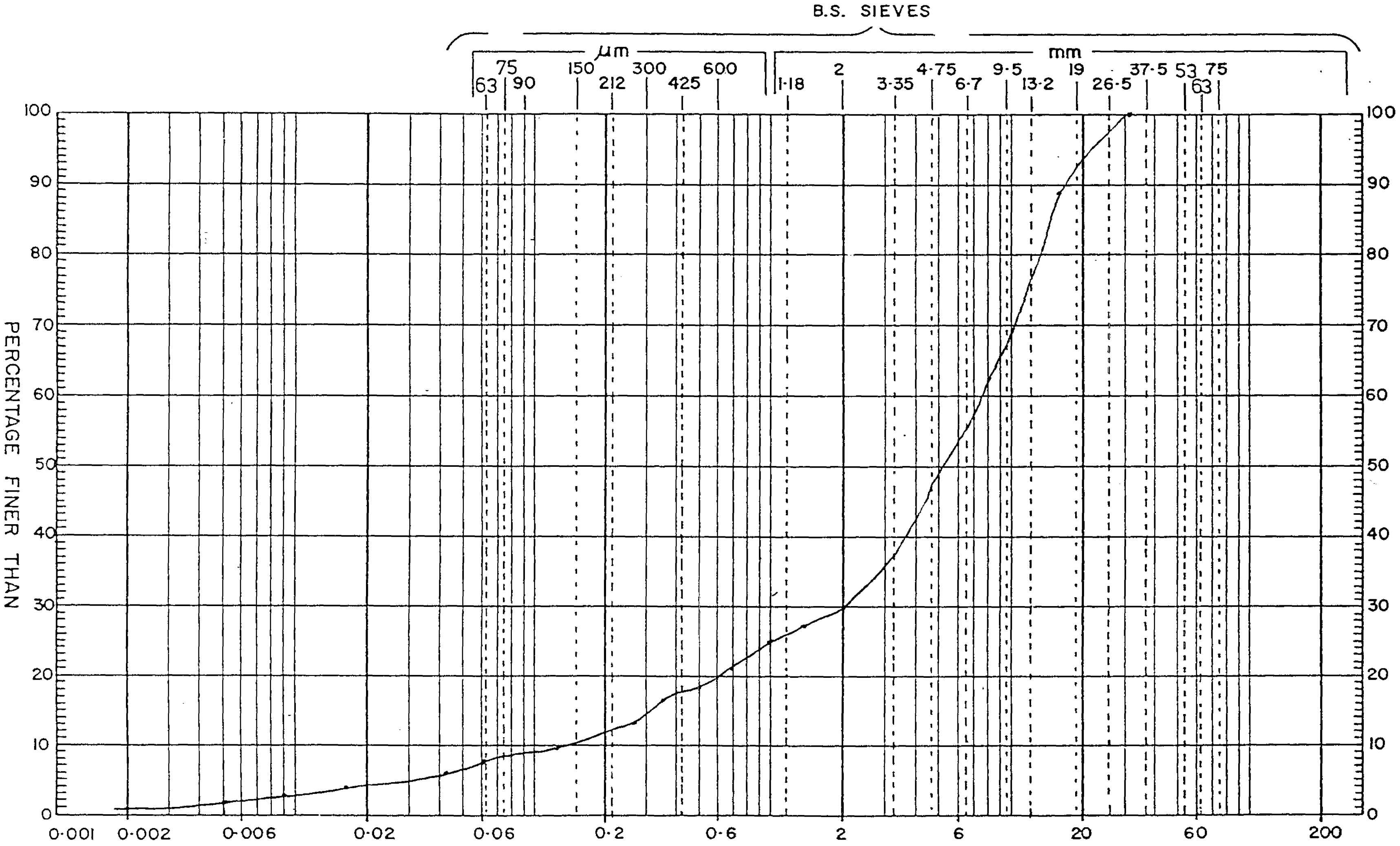
MOIST GREY CHARCOAL RICH CLAY

BASAL RIVER GRAVELS. VERY POORLY SORTED MOD. WEATHERED GRAVELS. BASAL CONTACT ATTITUDE 190/9° E

WAIKAWA STREAM ORIENTATION AT THIS LOCALITY 190° - 010°

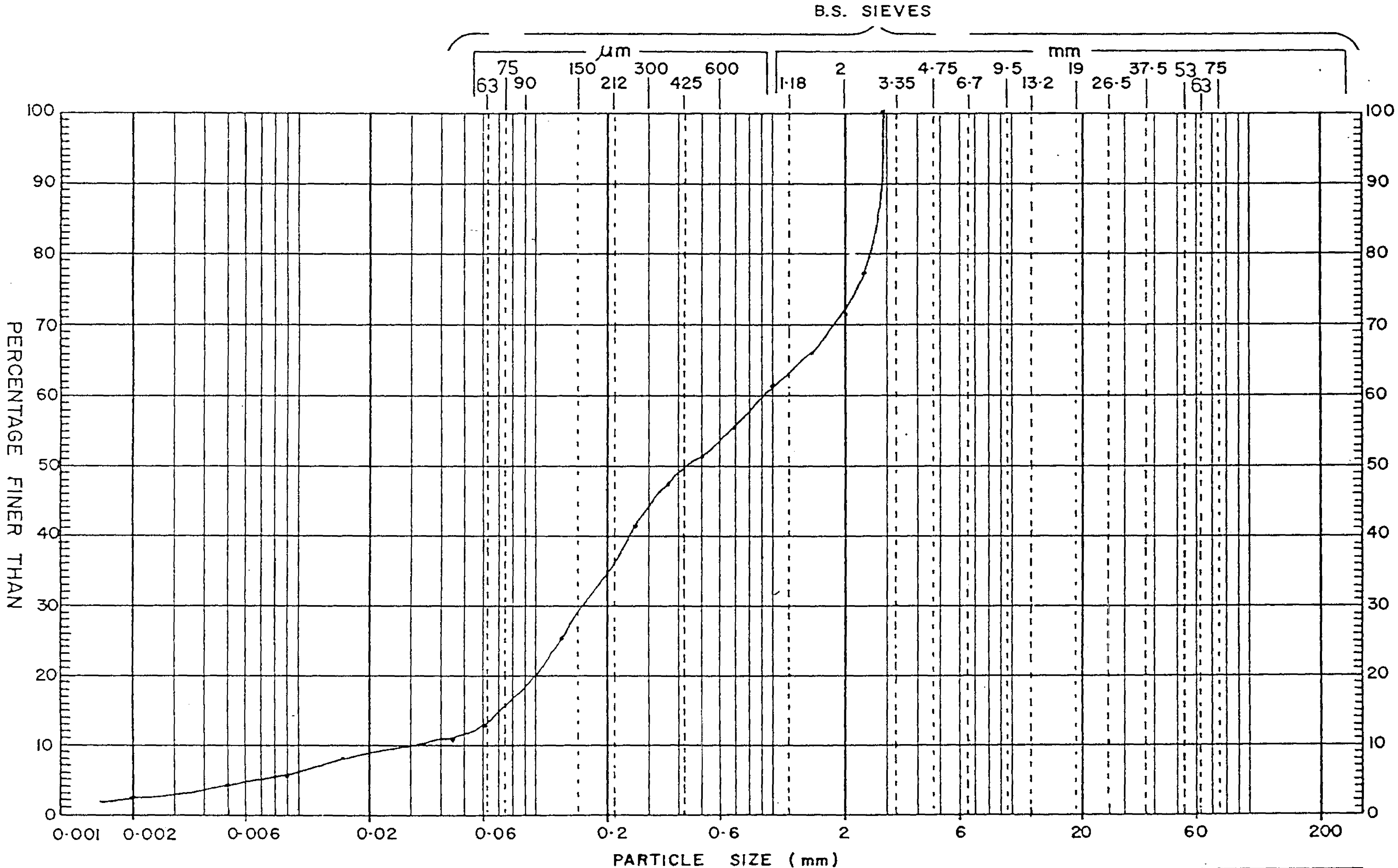
SAMPLING DEPTHS: LOCALITY WS1, WAIKAWA STREAM

INTERVAL (See measured section)	SAMPLE NUMBER
180-330 mm	WS1/1
460-580 mm	WS1/2
580-770 mm	WS1/3
770-910 mm	WS1/4
770-820 mm (charcoal horizon)	WS1/5
1010-1060 mm	WS1/6
1060-1100 mm	WS1/7
1100-1170 mm	WS1/8
1280-1370 mm	WS1/9
1390-1450 mm	WS1/10
1540-1600 mm	WS1/11
1540-1600 mm (wood)	WS1/12
1600-1830 mm	WS1/13
1780-1830 mm (wood)	WS1/14
1900-1930 mm	WS1/15
1900- 1920 mm	WS1/16



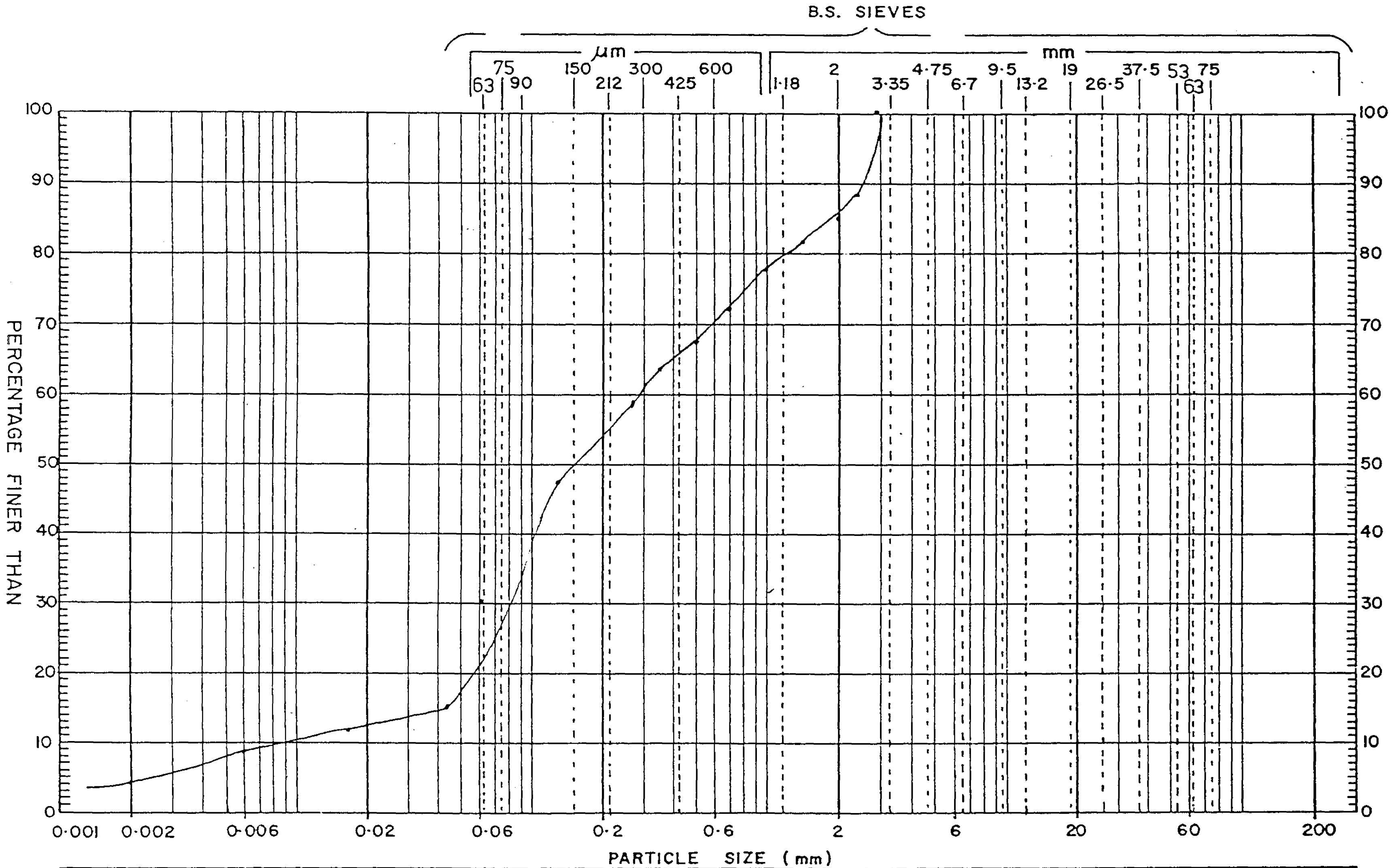
CLAY	FINE	MEDIUM	COARSE	FINE	MEDIUM	COARSE	FINE	MEDIUM	COARSE	V. COARSE	
	SILT			SAND			GRAVEL				

JOB:	SAMPLE No. WS1/3	NATURAL / ~~AIR DRIED/OVEN DRIED/UNKNOWN~~	TESTED BY:
	LOCATION: WS1	WET SIEVED, DRY SIEVED, PIPETTE, HYDROMETER	DATE: 6/89
		REMARKS	CHECKED BY:
	DEPTH:		DATE:



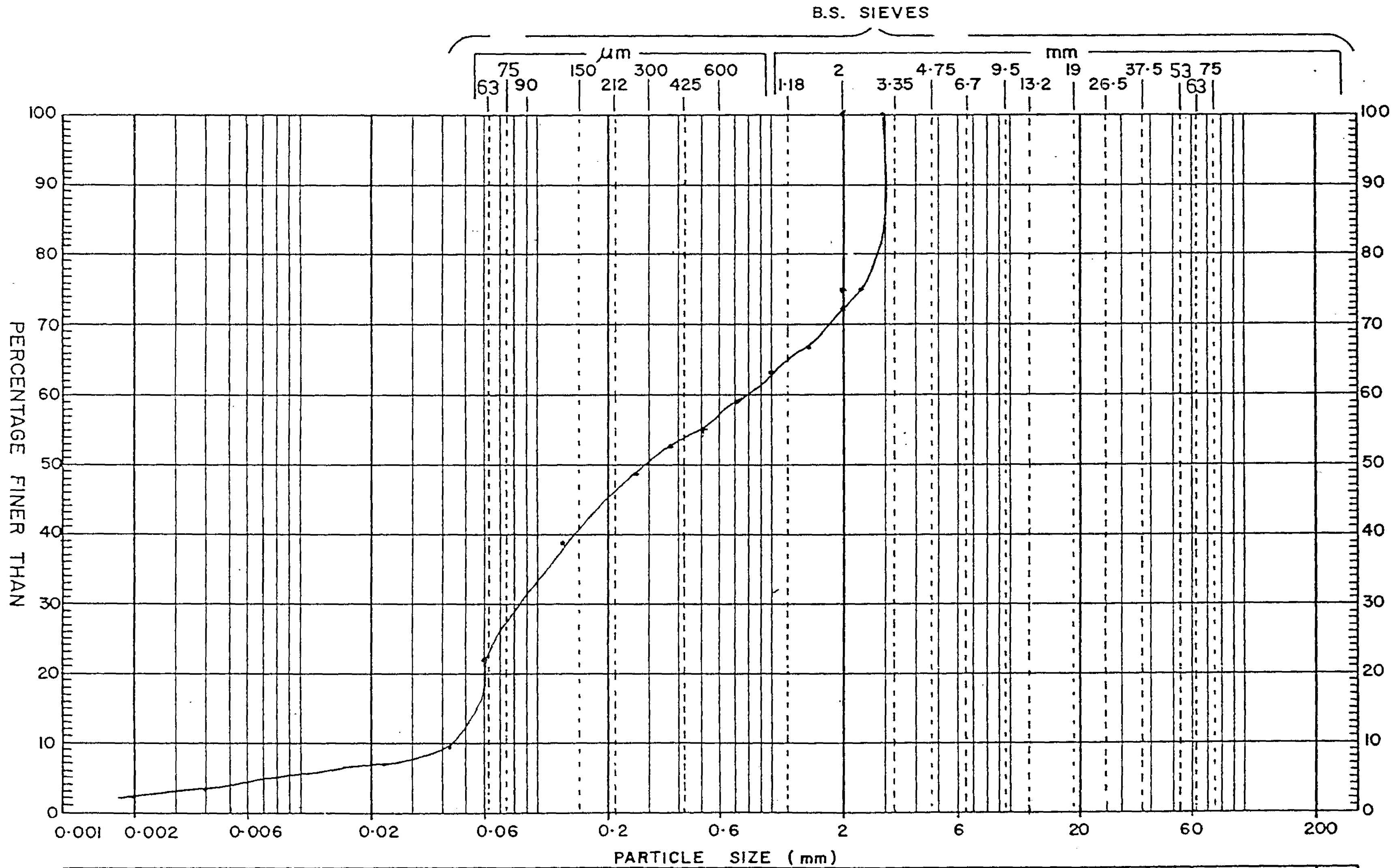
CLAY	FINE	MEDIUM	COARSE	FINE	MEDIUM	COARSE	FINE	MEDIUM	COARSE	V. COARSE	
	SILT			SAND			GRAVEL				

JOB:	SAMPLE No. WSi/4	NATURAL / ~~AIR DRIED/OVEN DRIED/UNKNOWN~~	TESTED BY:
	LOCATION: WSI	WET SIEVED, DRY SIEVED, PIPETTE, HYDROMETER	DATE: 6/89
		REMARKS	CHECKED BY:
	DEPTH:		DATE:



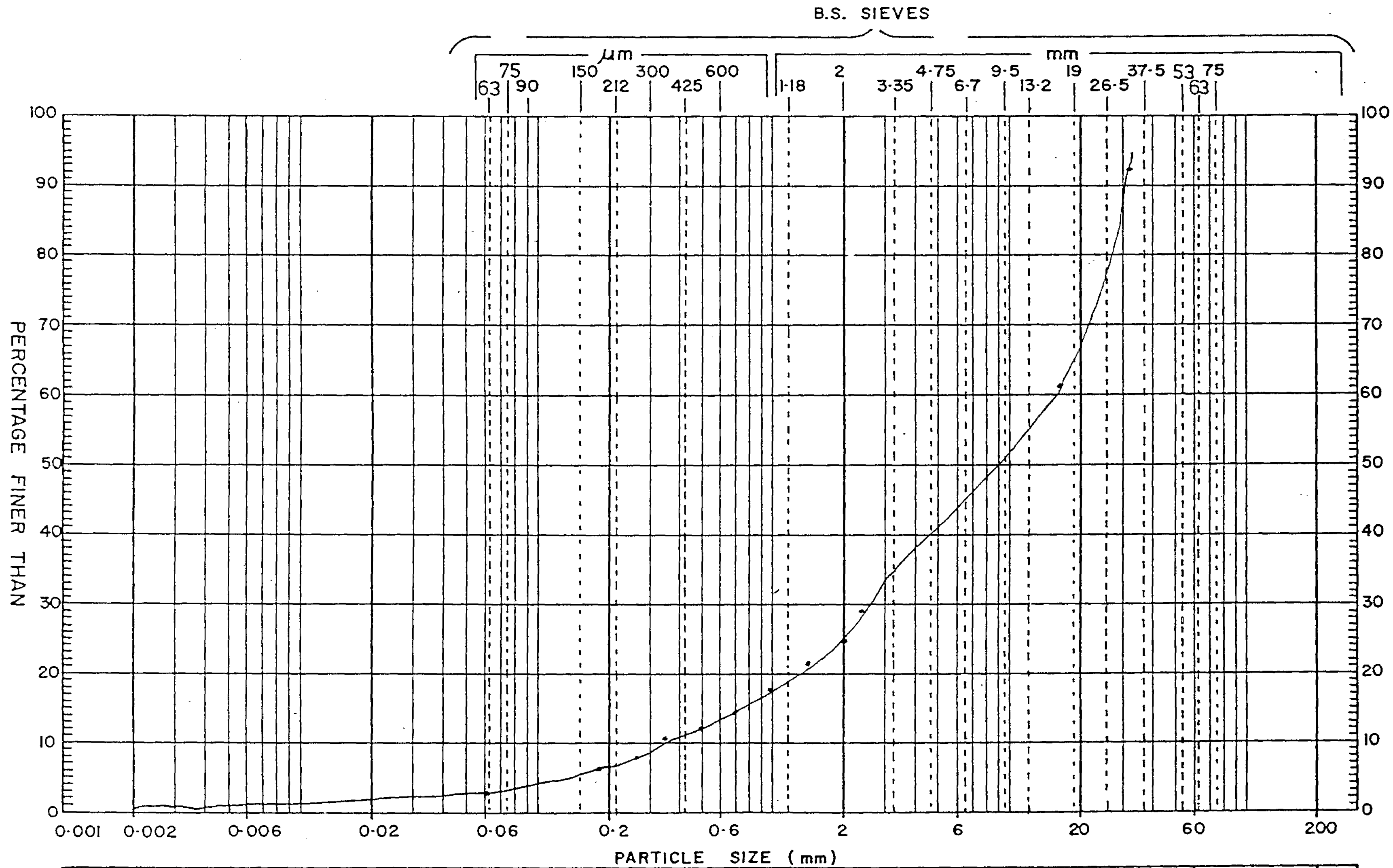
CLAY	FINE	MEDIUM	COARSE	FINE	MEDIUM	COARSE	FINE	MEDIUM	COARSE	V. COARSE	
	SILT			SAND			GRAVEL				

JOB:	SAMPLE No. WS1/16	NATURAL/~~AIR DRIED/OVEN DRIED/UNKNOWN~~	TESTED BY:
	LOCATION: WS1	WET SIEVED, DRY SIEVED, PIPETTE, HYDROMETER	DATE: 6/89
		REMARKS	CHECKED BY:
	DEPTH:		DATE:



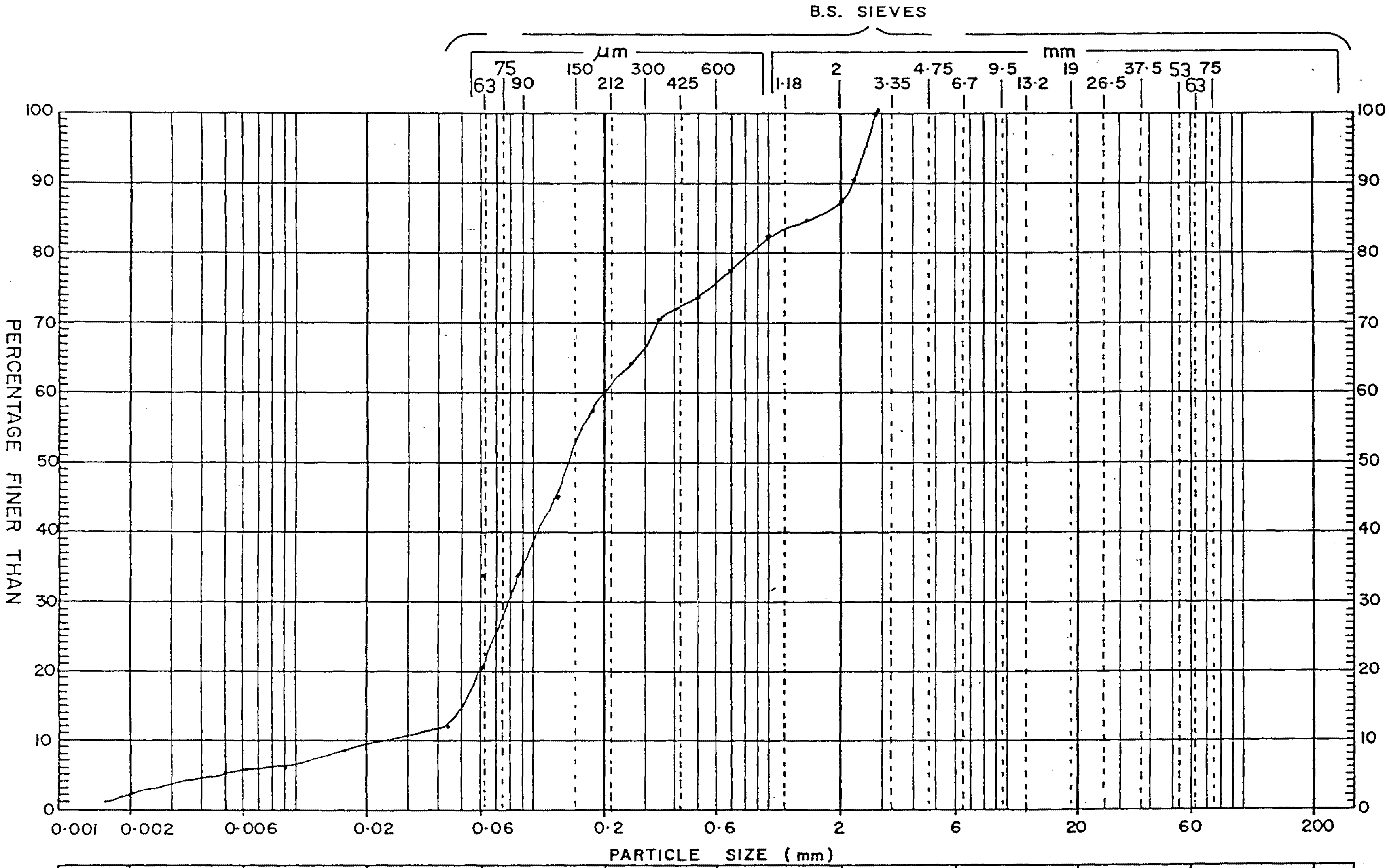
CLAY	FINE	MEDIUM	COARSE	FINE	MEDIUM	COARSE	FINE	MEDIUM	COARSE	V. COARSE	
	SILT			SAND			GRAVEL				

JOB:	SAMPLE No. WS1/1	NATURAL / ~~AIR DRIED/OVEN DRIED/UNKNOWN~~	TESTED BY:
	LOCATION: WS1/1	WET SIEVED, DRY SIEVED, PIPETTE, HYDROMETER	DATE: 6/89
		REMARKS	CHECKED BY:
	DEPTH:		DATE:



CLAY	FINE	MEDIUM	COARSE	FINE	MEDIUM	COARSE	FINE	MEDIUM	COARSE	V. COARSE
	SILT			SAND			GRAVEL			

JOB:	SAMPLE No. WS1/15	NATURAL ~~/AIR DRIED/OVEN DRIED/UNKNOWN~~	TESTED BY:
	LOCATION: WS1	WET SIEVED, DRY SIEVED, PIPETTE, HYDROMETER	DATE: 6/89
		REMARKS	CHECKED BY:
	DEPTH:		DATE:



CLAY	FINE	MEDIUM	COARSE	FINE	MEDIUM	COARSE	FINE	MEDIUM	COARSE	V. COARSE	
	SILT			SAND			GRAVEL				

JOB:	SAMPLE No. WS1/2	NATURAL/AIR DRIED/OVEN DRIED/UNKNOWN	TESTED BY:
	LOCATION: WS1	WET SIEVED, DRY SIEVED, PIPETTE, HYDROMETER	DATE: 6/89
		REMARKS	CHECKED BY:
	DEPTH:		DATE: